The Importance of Profiling

Perspectives on Individualized Endurance Testing and Training in Running-based Sports

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Summary

Running is among the most popular forms of physical activity due to its accessibility and health-promoting effects. Beyond its role in promoting cardiorespiratory fitness and reducing cardiovascular risk factors, running also serves as a fundamental component of many sports such as recreational or competitive running or many team sports. Thus, the same physiological adaptations that support health are systematically optimized in competitive contexts to maximize endurance and performance. In order to monitor adaptations to training and refine exercise prescription, traditional markers of endurance performance, such as aerobic capacity, commonly expressed as maximal oxygen uptake ($\dot{V}O_2max$), are typically evaluated.

In addition to those traditional markers, anaerobic-neuromuscular determinants have been recognized as important contributors to endurance performance, while still being mostly neglected in research and practice. In this context, maximal sprinting speed (MSS) plays a particularly relevant role, especially in middle-distance running and team sports, as it provides a performance 'buffer' at intensities exceeding the speed at $\dot{V}O_2max$ (maximal aerobic speed, MAS). The interaction, i.e., the speed difference, between MSS and MAS forms the anaerobic speed reserve (ASR), which integrates physiological, neuromuscular, and mechanical aspects of performance. Recent research suggests that ASR may outperform traditional markers such as $\dot{V}O_2max$ or MAS in predicting performance and has been suggested to categorize athletes into speed, hybrid, or endurance profiles, referred to as locomotor profiling. While several approaches exist for profiling athletes, such as locomotor profiling, their interrelationships and complementarity remain unclear. Therefore, the first aim of this thesis is to investigate the interaction between two common approaches for profiling athletes, including locomotor profiling, in order to better assess athlete strengths and weaknesses and support more specific training prescription.

However, the practical value of locomotor profiling relies on precise assessments of its components, MAS and MSS, which can be measured through various laboratory and field protocols. To ensure that changes in these markers reflect true physiological adaptations rather than measurement error or biological variability, valid and reliable testing methods are essential. No systematic overview of the validity and reliability of MAS and MSS testing in running-based sports is currently available. This gap limits practitioners in selecting and interpreting appropriate protocols. Consequently, the second aim of this thesis is to systematically review the validity and reliability of MAS and MSS tests in order to provide researchers and practitioners with evidence-based guidance for different applied contexts.

Many sports still rely on generalized training approaches, despite the substantial interindividual variability in acute and adaptive responses. This variability highlights the multifactorial nature of training responses and suggests that profiling could play an important role in explaining individual responses. In this regard, recent evidence points to locomotor profiling as a promising approach to account for differences in acute tolerance and longitudinal physiological responses to high-intensity interval training (HIIT). Moreover, conceptual frameworks suggest that endurance- and speed-type athletes, based on locomotor profiling, may respond differently to different HIIT formats, but these assumptions have not yet been systematically tested. Therefore, the third aim of this thesis is to investigate the role of locomotor profiles in explaining acute responses and chronic adaptations to different HIIT formats, thereby contributing to a more individualized approach to training prescription.

Regarding the first aim of this thesis, the findings of *Paper I* revealed clear differences across running disciplines, i.e. sprinters, 400-m runners, and middle-distance runners, in profiles based on the locomotor approach and a common physiological approach. While 400-m runners showed anaerobic power comparable to sprinters but aerobic capacity similar to middle-distance runners, their overall profile reflected a hybrid reliance on both energy systems. Moreover, correlational analyses between physiological and locomotor markers indicated that aerobic and anaerobic-mechanical markers were strongly related within their domains but largely independent between domains. Together, these findings suggest that physiological and locomotor profiling provide complementary perspectives and can effectively distinguish athlete subgroups. When methodological pitfalls of both approaches are considered, locomotor profiling has proven to be a solid framework for categorizing athletes and was chosen as the profiling approach in the subsequent studies.

The findings related to the second aim of this thesis highlight several key considerations for assessing MAS and MSS. *Paper II* and *III* emphasize that different definitions of MAS derived from $\dot{V}O_2$-kinetics during laboratory testing yield systematically different results, indicating that true MAS is assessed as the onset of the $\dot{V}O_2$ plateau. Moreover, most field-based tests such as incremental field tests or shuttle-runs over- or underestimate MAS, while time-trials adjusted to the athletes' fitness level or type of sports in terms of time or distance can serve as a simple field-test to estimate MAS. However, these tests need athletes to perform until physical exhaustion which is often not desired in times of high training load or competitions. Therefore, submaximal testing of maximal aerobic performance can optimize fitness testing. *Paper IV* identified age, sex, and the anaerobic lactate threshold as accurate submaximal predictors of maximal aerobic performance, while providing an online calculator as an accessible tool for applied settings. To complement the assessment of the locomotor profile, the findings of *Paper III* indicate that MSS can be accurately assessed with linear sprinting using radar, timing gates with 5–10 m split distances, or video analysis, whereas global or local positioning systems and treadmill sprinting currently lack sufficient validation. Collectively, these findings underscore the importance of

protocol selection, consistent MAS definitions, and appropriate measurement methods to ensure valid and reliable assessment for training prescription and performance monitoring. While the systematic review (*Paper III*) provides a solid overview of valid and reliable methods to assess MAS and MSS, *Paper IV* complements this by providing a practical tool for estimating maximal aerobic performance in applied settings.

Paper V shows that an athlete's locomotor profile is related to the tolerance to short-format HIIT. More specifically, endurance-type athletes (lower ASR and MSS) experienced higher load responses across biochemical, neuromuscular, and athlete-reported markers than speed-type athletes (higher ASR and MSS). These findings suggest that considering individual locomotor profiles when prescribing HIIT can help prevent overload and improve training individualization. More specifically, care should be taken, when prescribing short-format HIIT for endurance types to avoid undesirably high load. Moreover, *Paper VI* demonstrates that six weeks of HIIT or sprint-interval training (SIT) produce different physiological and locomotor adaptations depending on an athlete's locomotor profile. Speed-type athletes showed greater improvements chatin MAS and lactate thresholds than endurance types following both training formats, likely due to lower baseline MAS and higher adaptive potential. Changes in $\dot{V}O_2max$ were also profile-specific, with speed types responding better to HIIT and endurance types to SIT. Together with *Paper V*, these findings highlight that both acute responses and chronic adaptations to training are shaped by locomotor profiles, emphasizing the importance of individualized training strategies.

To conclude, this thesis underscores the value of profiling, and particularly locomotor profiling, for advancing individualized endurance testing and training in running-based sports beyond traditional markers of endurance performance. By combining physiological and locomotor perspectives, evaluating valid and reliable assessment methods, and applying profiling to guide training strategies, it contributes to a deeper understanding of performance characteristics and adaptive responses. At the same time, the applicability of profiling is shaped by methodological choices and population-specific factors, and training adaptations remain influenced by a complex interplay of biological and contextual determinants besides the locomotor profile. Thus, profiling should be seen as one key element among multiple factors driving performance. Looking ahead, future research should refine population-specific assessment protocols for MAS and MSS, further examine the predictive value of locomotor profiles for longitudinal monitoring of training load, and explore their integration into long-term athlete development models. In doing so, profiling approaches can continue to support the integration of individualized performance monitoring and training prescription.

Zusammenfassung

Der Laufsport gehört aufgrund seiner Zugänglichkeit und den gesundheitsfördernden Effekten zu den beliebtesten Formen körperlicher Aktivität. Neben der Förderung der kardiorespiratorischen Fitness und der Reduktion kardiovaskulärer Risikofaktoren, stellt das Laufen auch eine zentrale Komponente vieler Sportarten dar, sei es im Freizeit- oder Leistungslaufsport oder in zahlreichen Mannschaftssportarten. Die gleichen physiologischen Anpassungen, die die Gesundheit fördern, werden in wettkampforientierten Kontexten systematisch optimiert, um die Ausdauerleistungsfähigkeit zu maximieren. Um Trainingsanpassungen zu evaluieren und die Trainingssteuerung zu optimieren, werden traditionell Marker der Ausdauerleistung wie die aerobe Kapazität, üblicherweise erfasst als maximale Sauerstoffaufnahme ($\dot{V}O_2max$), oder Laktatschwellen ermittelt.

Neben klassischen Markern gelten auch anaerob-neuromuskuläre Determinanten als wichtige Einflussfaktoren der Ausdauerleistung, die in Forschung und Praxis jedoch bislang weitgehend unbeachtet bleiben. In diesem Zusammenhang kommt der maximalen Sprintgeschwindigkeit (MSS) eine besonders relevante Rolle zu, vor allem im Mittelstreckenlauf und in Teamsportarten, da sie oberhalb der Geschwindigkeit bei $\dot{V}O_2max$ (maximale aerobe Geschwindigkeit, MAS) einen „Leistungspuffer" darstellt. Die Interaktion bzw. die Differenz zwischen MSS und MAS bildet die anaerobe Geschwindigkeitsreserve (ASR), wodurch physiologische, neuromuskuläre und mechanische Leistungsaspekte kombiniert werden. Jüngste Forschungsergebnisse deuten darauf hin, dass die ASR klassische Marker wie $\dot{V}O_2max$ oder MAS bei der Vorhersage von Wettkampfleistungen übertreffen kann. Zudem wurde sie vorgeschlagen, um Athlet:innen in Schnelligkeits-, Hybrid- oder Ausdauerprofile einzuteilen (lokomotorisches Profiling). Während verschiedene Ansätze zum Profiling existieren, sind ihre Zusammenhänge und ihre Komplementarität bislang unklar. Das erste Ziel dieser Dissertation war es daher, die Interaktion zweier gängiger Profiling-Ansätze, darunter das lokomotorische zusammen mit physiologischem Profiling, zu untersuchen, um die Stärken und Schwächen von Athlet:innen optimal erfassen und die Trainingssteuerung spezifischer gestalten zu können.

Der praktische Nutzen des lokomotorischen Profilings hängt jedoch von präzisen Messungen seiner Komponenten MAS und MSS ab, die sowohl im Labor als auch im Feld bestimmt werden können. Um sicherzustellen, dass Veränderungen dieser Marker tatsächliche physiologische Anpassungen und nicht Messfehler oder biologische Variabilität widerspiegeln, sind valide und reliable Testmethoden unabdingbar. Bislang fehlt ein systematischer Überblick zur Validität und Reliabilität von MAS- und MSS-Tests im laufbasierten Sport. Diese Lücke erschwert Praktiker:innen die Auswahl und Interpretation geeigneter Protokolle. Das zweite Ziel dieser Dissertation war es daher, die Validität und

Reliabilität von MAS- und MSS-Tests systematisch zu überprüfen und evidenzbasierte Empfehlungen für Forschung und Praxis bereitzustellen.

Trotz erheblicher interindividueller Unterschiede in akuten Reaktionen und langfristigen Anpassungen, basieren Trainingsansätze in vielen Sportarten noch immer auf generischen Konzepten. Diese Variabilität verdeutlicht den multifaktoriellen Charakter von Trainingsreaktionen und legt nahe, dass Profiling eine wichtige Rolle bei der Erklärung individueller Unterschiede spielen könnte. In diesem Zusammenhang weisen aktuelle Studien auf das lokomotorische Profiling als vielversprechenden Ansatz hin, um Unterschiede in akuter Belastungstoleranz und physiologischen Langzeitanpassungen an hochintensives Intervalltraining (HIIT) zu berücksichtigen. Theoretische Annahmen legen zudem nahe, dass Ausdauer- und Schnelligkeitstypen, basierend auf dem lokomotorischen Profil, unterschiedlich auf verschiedene HIIT-Formate reagieren könnten. Diese Annahmen wurden jedoch bislang nicht empirisch überprüft. Das dritte Ziel dieser Dissertation war es daher, die Rolle lokomotorischer Profile bei der Erklärung akuter Reaktionen und chronischer Anpassungen an verschiedene HIIT-Formate zu untersuchen und damit zu einer individualisierten Trainingssteuerung beizutragen.

Bezüglich des ersten Ziels zeigen die Ergebnisse von *Studie I* deutliche Unterschiede zwischen den Laufdisziplinen Sprinter, 400 m und Mittelstrecke, in den Markern der lokomotorischen und physiologischen Profilingansätze. Während 400-m-Läufer:innen eine anaerobe Leistungsfähigkeit ähnlich der Sprinter:innen, jedoch eine aerobe Kapazität vergleichbar mit Mittelstreckler:innen aufwiesen, spiegelte ihr Gesamtprofil eine hybride Abhängigkeit von beiden Energiesystemen wider. Korrelationsanalysen verdeutlichen, dass aerobe und anaerob-mechanische Marker innerhalb ihrer Domänen eng verknüpft, zwischen den Domänen jedoch weitgehend unabhängig sind. Diese Ergebnisse legen nahe, dass physiologisches und lokomotorisches Profiling komplementäre Perspektiven liefern und Athlet:innengruppen zuverlässig unterscheiden können. Unter Berücksichtigung methodologischer Fallstricke erwies sich das lokomotorische Profiling basierend auf der ASR als robuste Methode zur Kategorisierung von Athlet:innen und wurde als Profilingansatz für die darauffolgenden Studien gewählt.

In Bezug auf das zweite Ziel verdeutlichen die Ergebnisse mehrere zentrale Aspekte bei der Erfassung von MAS und MSS. Die *Studien II* und *III* zeigen, dass unterschiedliche Definitionen von der im Labor erfassten MAS voneinander abweichen, wobei die MAS durch $\dot{V}O_2$-Kinetik ermittelt werden sollte. Zudem überschätzen oder unterschätzen viele Feldtests wie Stufentests oder Shuttle-Runs die MAS, während maximale Läufe auf Zeit oder Distanz, angepasst an Fitnessniveau oder Sportart, eine einfache Alternative darstellen können. Allerdings erfordern diese Tests eine Ausbelastung, was bei hoher Trainingsbelastung oder in Wettkampfphasen oft unerwünscht ist. Daher kann submaximales Testen der aeroben Kapazität die Diagnostik optimieren. *Studie IV* identifizierte Alter, Geschlecht und die anaerobe Laktatschwelle als präzise, submaximale Prädiktoren für die maximale aerobe Leistungsfähigkeit. Ergänzend dazu zeigten die Ergebnisse von *Studie III*, dass MSS valide über lineare Sprints mittels Radar, Lichtschranken (5–10-m Splits) oder Videoanalyse bestimmt werden kann, während globale oder lokale Positionssysteme und Laufband-Sprints aktuell nicht ausreichend validiert sind. Zusammenfassend unterstreichen diese Ergebnisse die Bedeutung einer konsistenten MAS-Definition und validierter Messmethoden für eine zuverlässige Leistungsdiagnostik und Trainingssteuerung auf Basis der ASR.

Bezüglich des dritten Ziels zeigt *Studie V*, dass das lokomotorische Profil die Toleranz gegenüber kurzformatigem HIIT beeinflussen kann. Konkret zeigten Ausdauertypen (niedrigere ASR und MSS) höhere Belastungsreaktionen in biochemischen, neuromuskulären und subjektiven Markern als Schnelligkeitstypen (höhere ASR und MSS). Insbesondere HIIT im Kurzformat für Ausdauertypen nur bedingt ins Training integriert, um eine unerwünscht hohe Belastung zu vermeiden. Dies legt nahe, dass die Berücksichtigung lokomotorischer Profile bei der HIIT-Planung Überlastungen vermeiden und die Trainingsindividualisierung verbessern kann. *Studie VI* zeigt zudem, dass sechs Wochen HIIT oder Sprint-Intervalltraining (SIT) je nach lokomotorischem Profil unterschiedliche Anpassungen hervorrufen. Schnelligkeitstypen verbesserten ihre MAS und Laktatschwelle in beiden Gruppen stärker als Ausdauertypen, vermutlich aufgrund niedrigerer Ausgangswerte und höherer Adaptationspotenziale. Auch $\dot{V}O_2max$-Veränderungen waren profilspezifisch: Schnelligkeitstypen reagierten stärker auf HIIT, Ausdauertypen stärker auf SIT. Insgesamt verdeutlichen diese Ergebnisse, dass akute Reaktionen und chronische Anpassungen durch das lokomotorische Profil geprägt werden kann, was die Bedeutung individualisierter Trainingsstrategien unterstreicht.

Abschließend unterstreicht diese Dissertation die Bedeutung des Profilings, insbesondere des lokomotorischen Profilings, für die Weiterentwicklung einer individualisierten Ausdauerdiagnostik und Trainingssteuerung im laufbasierten Sport über klassische Marker der Ausdauerleistung hinaus. Durch die Verknüpfung physiologischer und lokomotorischer Perspektiven, die Evaluation valider und reliabler Testmethoden sowie die Anwendung von Profiling zur Evaluation von Trainingsanpassungen leistet sie einen Beitrag zu einem vertieften Verständnis von Leistungsmerkmalen und Adaptationsprozessen. Zugleich wird die Anwendbarkeit des Profilings durch methodische Entscheidungen und populationsspezifische Faktoren beeinflusst, während Trainingsanpassungen weiterhin das Ergebnis eines komplexen Zusammenspiels biologischer und kontextueller Determinanten bleiben. Profiling sollte daher als ein wesentliches, jedoch nicht alleiniges Element unter den vielfältigen Faktoren betrachtet werden, die sportliche Leistung bestimmen. Zukünftige Forschung sollte populationsspezifische Protokolle zur Bestimmung von MAS und MSS ermitteln, den prädiktiven Wert lokomotorischer Profile für das longitudinale Belastungsmonitoring prüfen und deren Integration in langfristige Athlet:innenentwicklungen vorantreiben. Auf diese Weise kann Profiling nachhaltig zur Individualisierung von Leistungsdiagnostik und Trainingssteuerung beitragen.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

%ASR	Intensity relative to the anaerobic speed reserve
%HRmax12km/h	Fractional utilization of HRmax at 12 km/h
ANOVA	Analysis of variance
ASR	Anaerobic speed reserve
ATP	Adenosine triphosphate
CK	Creatine kinase
CMJ	Countermovement jump
CPET	Cardiopulmonary exercise testing
ċLamax	Maximal rate of lactate accumulation
e.g.	exempli gratia
GPS	Global positioning system
HIIT	High-intensity interval training
HR	Heart rate
HRmax	Maximal heart rate
HRR	Heart rate recovery
HRV	Heart rate variability
i.e.	id est
LIT	Low intensity training
LPS	Local positioning system
LT1	First lactate threshold
LT2	Second lactate threshold
MAS	Maximal aerobic speed
$MAS_{Plateau}$	Speed at the onset of the $\dot{V}O_2$-plateau

MAS_{30s}	First velocity of the 30-s interval of $\dot{V}O_2max$
MIT	Moderate intensity training
MSS	Maximal sprinting speed
RE	Running economy
RER	Respiratory exchange ratio
RPE	Rate of perceived exertion
RSI	Reactive strength index
SESOI	Smallest effect size of interest
SIT	Sprint interval training
SRR	Speed reserve ratio
SRSS	Short recovery and stress scale
T90%HRmax	Time spent above 90% of maximal heart rate
T90%$\dot{V}O_2max$	Time spent above 90% of maximal oxygen uptake
TOST	Two one-sided tests, i.e., equivalence testing
TT	Time trial
UMTT	Université de Montréal Track Test
vL4	Speed at a lactate concentration of 4 mmol/L
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_2max$	Maximal oxygen uptake
v_{peak}	Peak incremental treadmill or field test speed
VT1	First ventilatory threshold
VT2	Second ventilatory threshold
WA	World Athletics

List of Appendices

1 General Introduction

1.1 Preface

Running, often described as “a primordial human trait” (Gotaas, 2009), is not only one of the most widely practiced sports, with millions of runners worldwide, but also forms the foundation of many team sports. The global popularity of running can be attributed to its accessibility, health benefits, and the influence of cultural factors that make it a widespread activity embraced by diverse populations (Gotaas, 2009; Lee et al., 2014). While regular running training enhances health by improving cardiorespiratory fitness, i.e. maximal oxygen uptake ($\dot{V}O_2max$), and thereby reducing cardiovascular risk factors (Pedisic et al., 2020), in elite but also recreational sports the same physiological mechanisms are deliberately optimized through targeted training to maximize endurance performance. Besides $\dot{V}O_2max$, the key determinants for enhancing endurance performance are commonly described in terms of fractional utilization of $\dot{V}O_2max$ (or performance $\dot{V}O_2$) and running economy (RE) as depicted by the traditional model of Joyner and Coyle (2008).

In addition to the three traditional determinants of endurance performance, anaerobic and neuromuscular capacity have also been identified as important contributors determining endurance performance (Nummela et al., 2006; Paavolainen, Nummela, et al., 1999). The link between neuromuscular characteristics and movement economy indicates a potential indirect effect on endurance performance (Nummela et al., 2006). In this context, maximal sprinting speed (MSS) may play a particularly important role, especially in middle-distance running or team sports. A high MSS can provide a performance ‘buffer’ at intensities above athlete’s target race pace, as often performed at the finishing kick, or when team sports athletes need to perform repeated efforts at intensities above the speed at $\dot{V}O_2max$ (maximal aerobic speed; MAS) (Osborne et al., 2025; Sandford et al., 2021). More recently, the interplay between maximal anaerobic, neuromuscular, and mechanical capacities and maximal aerobic performance has attracted increasing attention for assessing running performance in the severe domain, that is, at intensities exceeding $\dot{V}O_2max$ or MAS, as typically observed in middle-distance running or in many team sports (Blondel et al., 2001; Sandford et al., 2021). In this regard, physiological profiling of athletes based on aerobic capacity (i.e. $\dot{V}O_2max$) and anaerobic power (i.e. maximal lactate accumulation rate; $\dot{c}Lamax$) has shown to be promising in evaluating performance (Mader & Heck, 1994). In addition, locomotor profiling based on the anaerobic speed reserve (ASR), reflecting the speed reserve between MSS and MAS, is suggested as a simple and accessible approach for profiling athletes (Sandford et al., 2021). Moreover, the ASR links physiological, neuromuscular, and mechanical determinants of endurance performance. More specifically, the ASR has previously shown to be a better predictor for performance than MAS or $\dot{V}O_2max$ alone (Blondel et al., 2001; Buchheit, Hader, et al., 2012) and is increasingly used for categorizing athletes into speed (high ASR), hybrid (moderate ASR), and endurance profiles (low ASR). Both methods, physiological and locomotor profiling, have shown promise for performance evaluation and training prescription (Hallam et al., 2022; Lundby et al., 2017; Quittmann et al., 2023; Sandford et al., 2021), yet their relationship and potential complementarity across running disciplines remain unclear. Therefore, the first aim of this thesis is to investigate the relationship between physiological and locomotor profiling across running disciplines. The findings of this study could be of interest for assessing strengths and weaknesses (e.g., for talent identification) or for more specific training prescription in running.

While the ASR is increasingly popular for profiling athletes or individualizing training, e.g., as a benchmark for high-intensity interval training (HIIT), its value depends on accurate measurements of MAS and MSS. Numerous tests have been developed to assess both MAS and MSS in the laboratory and in the field (Haugen & Buchheit, 2016; Lacour et al., 1991; Sandford et al., 2021). However, it is essential that these methods are valid and reliable to ensure observed changes reflect true adaptations rather than measurement error or biological variability (Simperingham et al., 2016). While previous reviews have examined the influence of testing conditions for sprint and aerobic assessments (Haugen & Buchheit, 2016; Bok & Foster, 2021), no systematic overview exists on the validity and reliability of methods to assess MAS and MSS in running-based sports. This leaves researchers and practitioners with limited guidance on protocol selection and interpretation. In this regard, the second aim refers to evaluating and systematically reviewing the validity and reliability of tests to assess MAS and MSS in running-based sports.

While the typical determinants of endurance performance are known and thereby the levers which should be pulled by specific training, many sports rely on a one-size-fits-all training approach. Even despite optimal training prescription, considerable interindividual variability in adaptive responses exists, underscoring the multifactorial interaction of biological and contextual determinants (Meyler et al., 2021). In this regard, profiling could play an important role in explaining individual acute responses and adaptations to training (Weakley et al., 2024). Emerging evidence suggests that profiling, and particularly locomotor profiling, may help explain interindividual differences in responses HIIT and guide program design. While some studies indicate that ASR predicts tolerance to high-intensity exercise and is associated with differing physiological responses (Buchheit, Hader, et al., 2012; Del Rosso et al., 2017), findings remain inconsistent, with other studies reporting no clear effects (Cipryan et al., 2017). It is further suggested that endurance-type athletes are thought to benefit more from long-format HIIT and higher volumes, while speed-type athletes may respond better to short-format HIIT or sprint specific work (Sandford et al., 2021). However, these assumptions remain largely conceptual and require experimental validation. Therefore, the third aim of this thesis is to examine the role of locomotor profiling in explaining acute responses and chronic adaptations to different HIIT formats. Understanding interindividual variability in training responses is essential for optimizing training strategies; thus, the present findings may underscore the importance of incorporating individual profiles when selecting training stimuli for performance development.

Overall, this thesis seeks to enhance the understanding of the importance of profiling athletes for individualized testing and training in running-based sports. The findings could thereby improve both research and practice by enhancing performance monitoring and guiding the prescription of optimal training stimuli.

1.2 Outline

Following the introduction of this thesis, its overall structure is outlined. It begins with a broad theoretical background, providing an overview of the central theme: determinants of endurance performance and adaptations to endurance training with a focus on individual acute responses and chronic adaptations and the role of profiling in running-based sports. This is followed by the presentation of the aims and scope, leading into the core section of the thesis, which consists of six studies examining specific aspects of profiling, particularly locomotor profiling, such as the discussion of different assessment methods as well as its importance in explaining individual differences in acute responses and chronic adaptations. Finally, the scope is widened again in a comprehensive discussion that integrates the findings, summarizes the key insights, and draws overarching conclusions. Overall, the thesis is structured based on an hourglass model as illustrated in Figure 1.1.

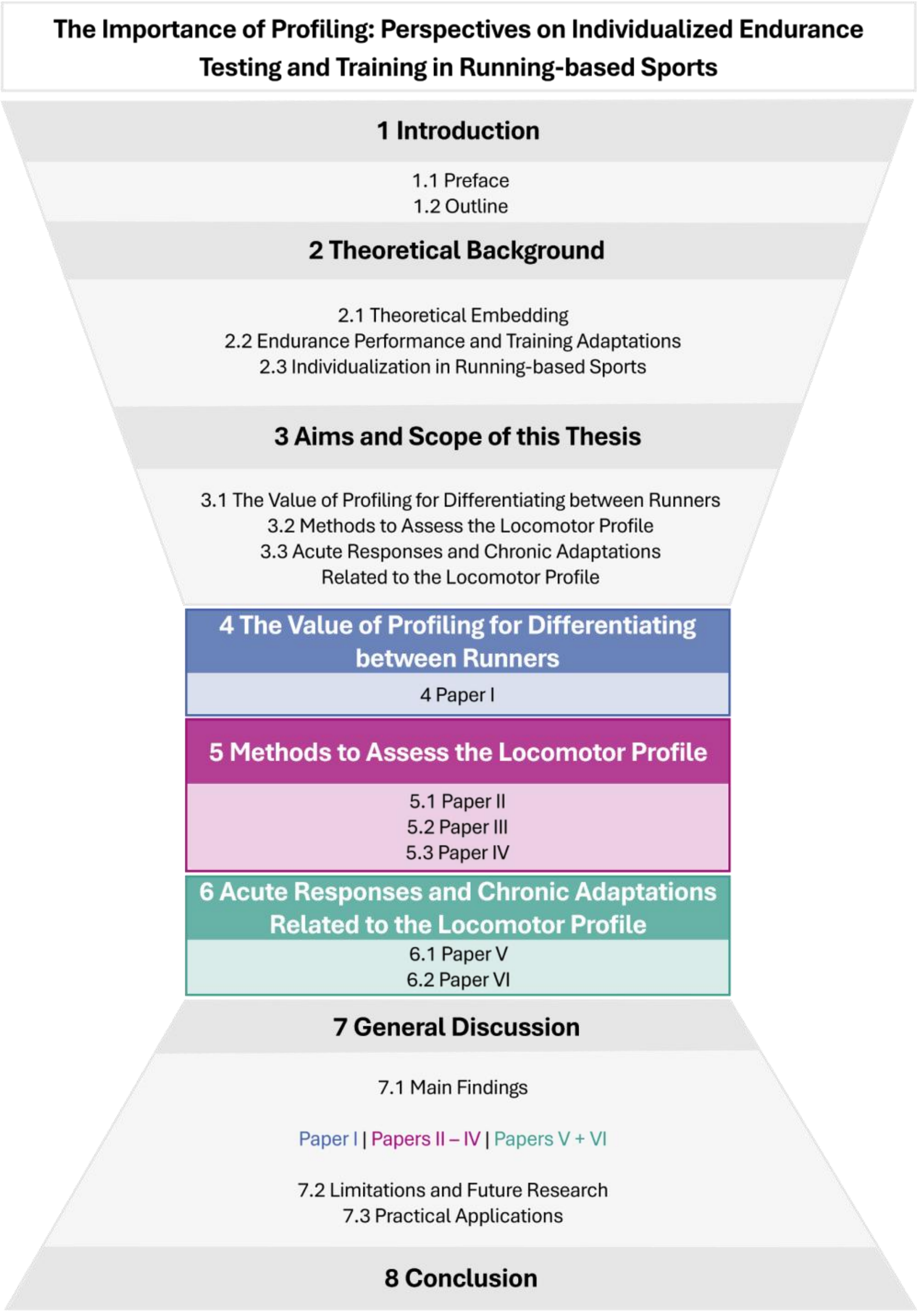

Figure 1.1: Structure of this thesis following an hourglass model.

Chapter 1: Introduction

In Chapter 1, the main topics of this dissertation are introduced, such as traditional determinants of endurance performance, the value of including anaerobic-mechanical markers in evaluating endurance performance, and the potential value of profiling based on several markers for explaining acute and chronic responses to training. Following the broad introduction of the topic, several research gaps are pointed out, leading to the three main aims of this thesis.

Chapter 2: Theoretical Background

Following the introduction of the underlying topic, Chapter 2 addresses the theoretical background of this thesis. The chapter starts by delineating the epistemological foundations and theoretical orientation of this thesis and the embedding within the wider discipline of sports science to contextualize it within a broader academic framework. After defining the motor ability endurance, the traditional determinants of endurance performance are presented and extended by considering novel markers of endurance performance. Moreover, adaptations to endurance training in general as well as the individuality of acute and chronic responses to training are addressed, followed by a description of how profiling athletes might add value in testing and training endurance performance.

Chapter 3: Aims and Scope

Building on the identified research gaps and the theoretical framework presented in Chapter 2, Chapter 3 sets out the aims and scope of this thesis.

Chapter 4: The Value of Profiling for Differentiating between Runners

Addressing the first main aim of this thesis elaborated in Chapter 3, Chapter 4 presents Paper I, which evaluates the relationship between physiological and locomotor profiles and their significance for differentiating between different running disciplines.

Paper I:

Thron, M., Woll, A., Doller, L., Quittmann, O. J., Härtel, S., Ruf, L., & Altmann, S. (2024). Physiological and Locomotor Profiling Enables to Differentiate Between Sprinters, 400-m Runners, and Middle-Distance Runners. *The Journal of Strength & Conditioning Research*, 10, 1415-1427. https://doi.org/10.1519/JSC.0000000000004801

Chapter 5: Methods to Assess the Locomotor Profile

Presented in Chapter 5, Papers II–IV investigated different methods to assess the locomotor profile, focusing on valid and reliable measurement of MAS and MSS as key components of the ASR. Paper II evaluated the validity of field tests against treadmill testing to refine MAS assessment, while Paper III systematically reviewed the literature regarding validity and reliability of MAS and MSS testing methods. Paper IV examined submaximal predictors of peak incremental running test speed, a proxy of maximal aerobic performance, as practical alternatives to exhaustive testing protocols in soccer players.

Paper II:

Thron, M., Woll, A., Klos, L., Härtel, S., Ruf, L., Kloss, C., & Altmann, S. (2022). Overestimation of maximal aerobic speed by the Université de Montréal track test and a 1500-m-time trial in soccer. *Frontiers in Physiology*, 13. https://doi.org/10.3389/fphys.2022.1023257

Paper III:

Thron, M., Dueking, P., Ruf, L., Haertel, S., Woll, A., & Altmann, S. (2024). Assessing Anaerobic Speed Reserve: A Systematic Review on the Validity and Reliability of Methods to Determine Maximal Aerobic Speed and Maximal Sprinting Speed in Running-based Sports. PLoS ONE, 19. https://doi.org/10.1371/journal.pone.0296866

Paper IV:

Thron, M., Buchheit, M., Ruf, L., Sondermann, Y., Woll, A., & Altmann, S. (under review). Submaximal predictors of peak incremental running test speed as a proxy of maximal aerobic performance in soccer players.

Chapter 6: Acute Responses and Chronic Adaptations Related to the Locomotor Profile

Outlined in Chapter 6, Papers V and VI examined how locomotor profiles influence both acute responses and chronic adaptations to interval training. Paper V investigated associations between MAS, MSS, and ASR with acute physiological, biochemical, neuromuscular, and perceptual responses to MAS-based HIIT in trained runners, aiming to clarify individual tolerances. Paper VI compared adaptations to six weeks of HIIT or SIT, and tested whether baseline locomotor profiles moderated these outcomes, thereby exploring their utility for tailoring individualized training prescriptions.

Paper V:

Thron, M., Ruf, L., Buchheit, M., Härtel, S., Woll, A., & Altmann, S. (2024). Anaerobic speed reserve and acute responses to a short-format high-intensity interval session in runners. *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2024.12.012

Paper VI:

Thron, M., Sondermann, Y., Ruf, L., van Hooren, B., Düking, P., Wehdemeier, L., Buday, L., Woll, A., & Altmann, S. (under review). Locomotor profile influences physiological and locomotor adaptations after six weeks of high-intensity or sprint interval training in male and female runners.

Chapter 7: General Discussion

The general discussion in Chapter 7 summarizes and discusses the main findings of Papers I–VI. This includes a discussion based on the current state of literature as well as the studies' limitations. Following, open research questions as well as practical applications of the thesis' findings are depicted.

Chapter 8: Conclusion

This thesis closes with a final conclusion which again takes a broader perspective of the importance of profiling for individualized testing and training.

2 Theoretical Background

After providing a theoretical framework and classifying this thesis in the field of sports science, Chapter 2 provides an overview of endurance in general. Subsequently, key determinants of endurance performance and the adaptations to endurance training are outlined. It then considers individual acute responses and chronic adaptations before concluding with a consideration of physiological and locomotor profiling as tools for individualization in endurance sports, thereby evaluating the research gaps addressed in this thesis.

2.1 Theoretical Embedding

This subchapter situates the present thesis within a theoretical and scientific-philosophical framework, clarifying the epistemological background, methodological approach, and the rationale for knowledge generation. In doing so, it establishes the foundation for understanding how the research questions were derived, how the studies were conducted, and how conclusions are drawn.

Scientific research in sports science can be approached from multiple orientations, including social-behavioral, medical-scientific, historical-philosophical, and economic-political perspectives (Schröder & Dose, 2010). The present thesis aligns with the medical-scientific orientation in the field of exercise physiology, focusing on objectively measurable physiological and locomotor characteristics in running-based sports. The overarching aim is applied and interdisciplinary research, linking theoretical models of endurance performance and locomotor profiling with practical implications for training prescription and performance monitoring (Hopkins, 2002; Schröder & Dose, 2010). Therefore, the epistemological position of this thesis can be classified as empirical. Empirical research relies on observable, measurable phenomena that can be quantified, documented, and reproduced (Schröder & Dose, 2010). In this context, athlete performance was examined using standardized laboratory and field tests to evaluate physiological markers (e.g., $\dot{V}O_2max$, $\dot{c}Lamax$) and locomotor variables (e.g., MAS, MSS, ASR) as well as biochemical, cardiorespiratory, neuromuscular, or athlete-reported load markers across different running-based sports.

From a philosophical perspective, this thesis adopts a critical rationalist stand point (Chalmers, 2001). Critical rationalism assumes that no scientific knowledge can be regarded as absolutely certain; all statements are provisional and must be subject to continuous scrutiny. Accordingly, scientific progress is achieved not through verification but through falsification: observations are used to challenge and potentially refute hypotheses rather than to confirm them (Popper, 1935). Falsification emphasizes the development of specific, testable, and provisional models. The empirical focus of this dissertation relies on the precise measurement and analysis of physiological and locomotor variables. Following, the theoretical background of endurance performance and training guided the derivation of research aims across six studies. These included laboratory as well as field tests for cross-sectional comparison of physiological and locomotor profiles (Paper I), retrospective, cross-sectional, and systematic evaluation of assessment methods (Papers II–IV), and intervention studies assessing acute and chronic adaptations to HIIT (Papers V–VI). Each aim was subjected to rigorous empirical testing, enabling falsifiable conclusions about individualized testing and training based on profiling. Quantitative analyses, including linear models as well as linear mixed models, correlation analyses, k-fold cross-validation, and equivalence testing, were applied to examine relationships between physiological and locomotor variables, evaluate moderation on acute and chronic adaptations to training, and validate prediction accuracy. In addition, systematic review methodology was employed to critically evaluate the validity and reliability of MAS and MSS assessment protocols across running-based sports, ensuring a rigorous foundation for subsequent experimental studies. Observations were carefully documented, and results were interpreted in light of prior knowledge, theoretical expectations, and methodological constraints. This iterative approach enables the generation of knowledge that is scientifically robust and practically relevant, supporting evidence-based profiling, individualized training prescription, and performance monitoring in running-based sports (Chalmers, 2001).

In sum, this thesis focuses on physiological and locomotor characteristics in athletes, applies empirical methods across cross-sectional, retrospective, and intervention designs, and emphasizes generalizable patterns while maintaining methodological rigor and critical impartiality (Hopkins, 2002; Schröder & Dose, 2010). By integrating multiple methodological approaches, this thesis aims to provide a comprehensive framework for understanding, measuring, and applying locomotor profiling in practice and future research.

2.2 Endurance Performance and Training Adaptations

Among the motor abilities, endurance is considered an energetically determined (conditional) ability, similar to strength and speed, whereas speed additionally encompasses coordinative components (Bös, 1994). Moreover, endurance can be described as the capacity to maintain performance and withstand physical and mental fatigue during extended periods of exercise (Hollmann & Strüder, 2009). In this context, endurance is often referred to as aerobic endurance since the primary source of energy during prolonged exercise is derived from the aerobic metabolism. To achieve performance by muscle work, the availability of adenosine triphosphate (ATP), as the universal provider of energy, is necessary. During extended efforts, ATP is predominantly resynthesized via oxidative phosphorylation of carbohydrates and fatty acids (Heck et al., 2022). While for longer exercise such as marathon running, the energy supply relies mainly on the aerobic metabolism, in shorter events with a higher relative intensity such as middle-distance running, the anaerobic metabolism gains more importance. During higher intensities, ATP supply is assured by intramuscular ATP, phosphocreatine, and anaerobic glycolysis of carbohydrates (Hollmann & Strüder, 2009). Since the outcome of endurance exercise in high-level but also recreational sports is almost always performance, e.g., race time in running events or running distance in team sports matches, knowing and quantifying the determinants of endurance performance is crucial for optimizing testing and training. Therefore, the following subsections describe and discuss the determinants of endurance performance and the adaptations of these determinants by training.

2.2.1 Determinants of Endurance Performance

Endurance performance depends largely on the body's ability to transport and utilize oxygen efficiently to resynthesize ATP during prolonged exercise. The gold-standard measure for this capacity is the maximal oxygen uptake ($\dot{V}O_2max$), which reflects the highest rate at which oxygen can be consumed during intense effort. As a marker of cardiovascular and respiratory function, $\dot{V}O_2max$ is typically used to assess cardiorespiratory fitness (Bassett & Howley, 2000). Indeed, strong correlations between $\dot{V}O_2max$ and race outcomes have been reported across several long distances (Foster, 1983; Noakes et al., 1990). However, in highly trained athletes, the association between $\dot{V}O_2max$ and performance is relatively poor (Conley & Krahenbuhl, 1980; Sjodin & Svedenhag, 1985). Consequently, $\dot{V}O_2max$ is a valuable metric in predicting and evaluating endurance performance, it represents only part of a broader physiological characterization.

Additionally, the energy cost of running at a submaximal speed, also referred to as running economy (RE), is considered an important determinant of endurance performance and plays a key role in converting $\dot{V}O_2$ performance into running speed (Barnes & Kilding, 2015a; Jones, 2023). Among elite runners with similar $\dot{V}O_2max$, RE has shown to be a better predictor for running performance than $\dot{V}O_2max$ (Saunders et al., 2004). RE is understood as a multifaceted concept that reflects the combined influence of metabolic, cardiorespiratory, biomechanical, and neuromuscular factors during submaximal running (Barnes & Kilding, 2015a). Building on this, the concept of maximal aerobic speed (MAS) was introduced as an integrative variable that combines $\dot{V}O_2max$ and RE into a single measure, originally defined as the ratio between oxygen uptake and the cost of running (Di Prampero et al., 1986). MAS captures aerobic differences between runners more effectively than either $\dot{V}O_2max$ or RE alone, thereby providing a more comprehensive explanation of performance variability (Billat & Koralsztein, 1996). Subsequently, MAS was defined and determined as the speed at $\dot{V}O_2max$ (see Figure 2.1) (Billat et al., 1996).

Moreover, differences between athletes in $\dot{V}O_2max$ for similar performances and different times to exhaustion at an intensity of $\dot{V}O_2max$ indicate the importance of sustaining a high fractional utilization of $\dot{V}O_2max$ during an effort or race (Kumagai et al., 1982). However, more recent research is doubting the importance of fractional utilization of $\dot{V}O_2max$ for endurance performance due to similar fractional utilization of $\dot{V}O_2max$ at the second lactate threshold between different levels of performance (Johansen et al., 2025). The fractional utilization of $\dot{V}O_2max$ is not only dependend on $\dot{V}O_2max$ per se but also on performance at metabolic thresholds, such as the speed at aerobic and anaerobic thresholds (Seiler, 2010). Metabolic thresholds are typically assessed via breathing gas analyses or blood lactate measurements. The first metabolic threshold aims to describe the intensity at which energy supply is predominantly maintained by the aerobic metabolism (aerobic threshold) and is typically determined as the first increase in blood lactate (e.g., lactate threshold 1, LT1) or as the increase of ventilation in relation to $\dot{V}O_2$ (e.g., ventilatory threshold 1, VT1) (Faude et al., 2009; Heck et al., 2022). The second metabolic threshold (anaerobic threshold) refers to the maximal metabolic steady-state of aerobic and anaerobic metabolism. At intensities above, blood lactate starts to accumulate further (above lactate threshold 2, LT2) and the ventilation increases in relation to the carbon dioxide production (above ventilatory threshold 2, VT2) (Meyer, Lucia, et al., 2005). Moreover, the anaerobic threshold is strongly linked to the performance in 10,000-m races or can typically be sustained for a time period of 45–60 min (Heck et al., 2022; Roecker et al., 1998).

While $\dot{V}O_2max$, fractional utilization, and RE are considered the traditional determinants of endurance performance, anaerobic and neuromuscular (non-oxidative) factors have gained increasing attention as complementary determinants (Jones, 2023; Paavolainen, Nummela, et al., 1999). The relationship between neuromuscular characteristics and movement economy suggests a potential influence on performance (Nummela et al., 2006). In this regard, maximal sprinting speed (MSS; see Figure 2.1) may influence performance, especially in middle-distance running, as it provides a performance ‘buffer’ at intensities above athlete’s target race pace, as often performed at the finishing kick or when team sports athletes need to perform repeated efforts at intensities above MAS (Osborne et al., 2025; Sandford et al., 2021). In addition, the maximal lactate accumulation rate ($\dot{c}Lamax$) aims to reflect the power of anaerobic glycolysis. A high $\dot{c}Lamax$ can elevate lactate production at a given workload, which in turn lowers the maximal metabolic steady-state and fractional utilization of $\dot{V}O_2max$ that can be sustained (Mader, 2003). While $\dot{c}Lamax$ is negatively associated with 5,000-m running performance, a higher $\dot{c}Lamax$ has shown to benefit the ‘finishing-kick’ in this specific race (Quittmann et al., 2023). Moreover, for intensities above the metabolic threshold (e.g. during 5,000-m running), the curvature constant (D’) as the potential distance that can be covered above the anaerobic threshold, becomes an important factor for sustaining performance (Nixon et al., 2021).

More recently, the combination of maximal aerobic performance such as MAS and maximal neuromuscular and mechanical capabilities such as MSS has gained interest in evaluating running performance in the severe running domain, i.e., above $\dot{V}O_2max$ or MAS as during middle-distance running (Blondel et al., 2001; Sandford, Kilding, et al., 2019; Sandford et al., 2021). While the accuracy and significance of measures for the anaerobic metabolism (e.g., $\dot{c}Lamax$) are yet in doubt, the speed difference between MSS and MAS, i.e., the anaerobic speed reserve (ASR; see Figure 2.1), can provide valuable insights into the mechanisms underlying high-speed and power performance (Sandford et al., 2021).

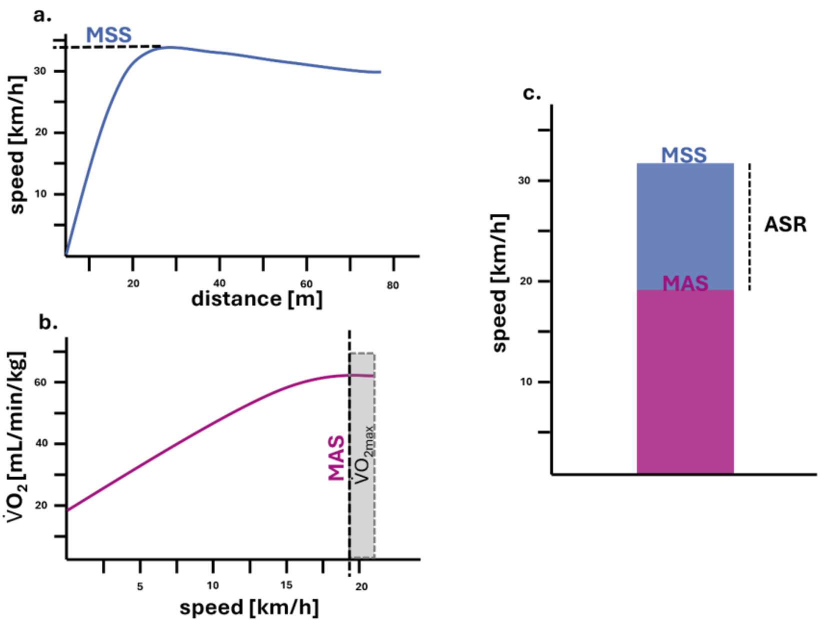

Figure 2.1: Exemplary assessment of MSS (a.), MAS (b.) and ASR (c.). MSS – maximal sprinting speed; MAS – maximal aerobic speed; $\dot{V}O_2max$ – maximal oxygen uptake; ASR -anaerobic speed reserve.

Recent research indicates that physiological and performance determinants may shift under fatigue during extended exercise (Barrett & Maunder, 2025; Maunder et al., 2021; Zanini et al., 2025). Based on this phenomenon, it was suggested to expand endurance performance determinants by ‘durability’ or ‘physiological resilience’, the capability to sustain steady-state performance and resist fatigue in prolonged events (Jones, 2023; Jones & Kirby, 2025; Maunder et al., 2021). Figure 2.2 illustrates the influence and interrelations of the determinants of running performance based on the models of Joyner and Coyle (2008), Jones (2023), and Paavolainen, Häkkinen, et al. (1999).

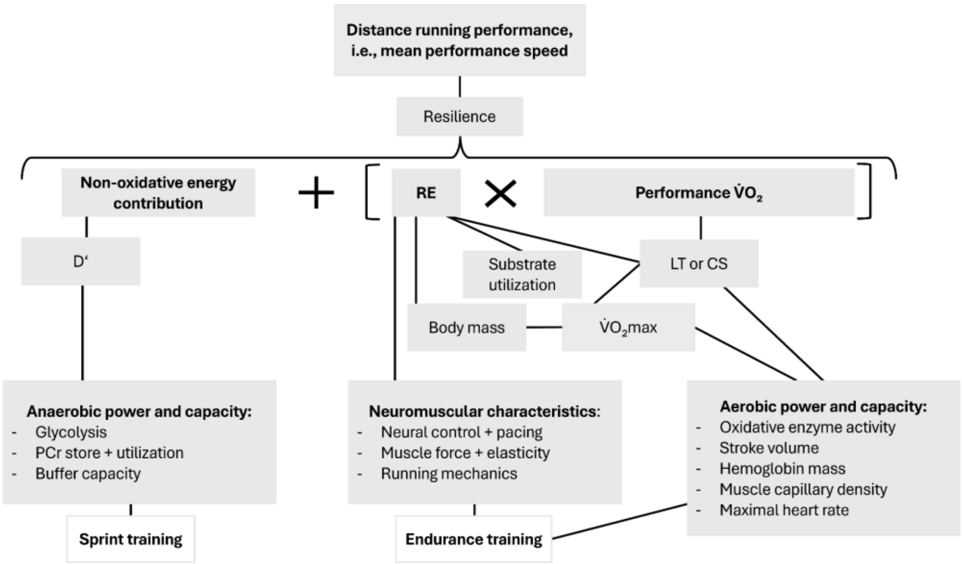

Figure 2.2: Determinants of running performance, adapted from Jones (2023); Joyner and Coyle (2008); Paavolainen, Häkkinen, et al. (1999). RE – running economy; $\dot{V}O_2$ – oxygen consumption; D' – curvature constant; LT – lactate threshold; CS – critical speed; $\dot{V}O_2max$ – maximal oxygen uptake.

Based on the presented model (Figure 2.2), running performance, i.e. mean performance speed, can be calculated using the contribution to energy supply of non-oxidative metabolism, RE, and fractional utilization of $\dot{V}O_2max$ (Jones, 2023; Joyner & Coyle, 2008; Paavolainen, Häkkinen, et al., 1999). Resilience reflects that these determinants are not stable during prolonged exercise, which explains interindividual performance differences while the determinants remain similar between athletes (Jones, 2023). The influence of training and affecting factors on these determinants are summarized and discussed in the following chapter (Chapter 2.2.2).

2.2.2 Adaptations to Endurance Training

Endurance training induces stress on the biological system aiming to achieve acute responses and long-term adaptations in performance determining and enhancing factors (Lambert, 2016). Besides volume and frequency, the intensity of the exercise is crucial as it strongly influences the adaptations. Training intensity is often divided into low (LIT), moderate (MIT), and high (HIIT) intensity training zones, typically defined by metabolic thresholds (see Figure 2.3) (Coates et al., 2023; Meyer, Lucia, et al., 2005; Seiler & Tønnessen, 2009). LIT involves low lactate concentrations (~baseline; <first threshold or 2 mmol/L), 60–80% maximal heart rate (HRmax), and low perceived effort (rating of perceived exertion; RPE 1–4 of 10). In elite distance runners, LIT, often included as high-

volume training, makes up the major part of endurance training, often in continuous sessions >40 min, with duration varying by type of sports (e.g. cycling or running) (Coates et al., 2023; Haugen et al., 2022; Seiler & Tønnessen, 2009). MIT occurs between the first and second metabolic thresholds, with lactate concentrations of 2–4 mmol/L, 80–90% of HRmax, and moderate effort (RPE 5–6 of 10). It includes continuous work (20–60 min) or intervals (1–15 min) totaling >30 min, and can be sustained for prolonged periods, even in events like marathon (Haugen et al., 2022; Seiler & Tønnessen, 2009). HIIT is typically performed above the second metabolic threshold, often in long intervals (1–6 min) or microintervals (e.g., 30 s) designed to maximize time ≥90% $\dot{V}O_2max$. It elicits high lactate concentrations (4–10 mmol/L), 90–100% HRmax, and high perceived effort (RPE 7–10 of 10), with typical accumulated time of 15–30 min (Coates et al., 2023; MacInnis & Gibala, 2017). At the extreme, sprint intervals (SIT) exceed $\dot{V}O_2max$ and MAS, ranging from short 30-s sprints to all-out efforts up to MSS with varying lactate concentrations and HR depending on the duration of sprints and rest intervals (Rosenblat et al., 2022; Sloth et al., 2013).

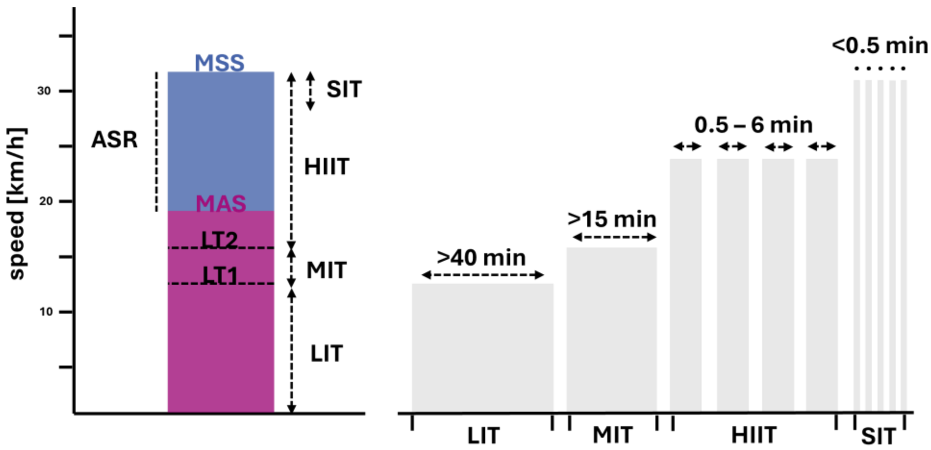

Figure 2.3: Speed ranges for training zones (adapted from Buchheit & Laursen, 2013a; Meyer, Lucia, et al., 2005). MSS – maximal sprinting speed; MAS – maximal aerobic speed; ASR -anaerobic speed reserve, LT1 – lactate threshold 1; LT2 – lactate threshold 2; SIT – sprint interval training; HIIT – high-intensity interval training; MIT – moderate intensity training; LIT – low intensity training.

Acute Responses

An acute bout of endurance exercise causes immediate, transient physiological and psychobiological changes that persist only for the duration of exercise and shortly thereafter (Lambert, 2016). HR, stroke volume, and cardiac output increase proportionally to intensity, with maximal cardiac output reaching 20–40 L/min depending on the training status (Gledhill et al., 1994). Blood is redistributed toward active muscles, and the arteriovenous oxygen difference increases due to greater extraction by muscle tissue (Gledhill et al., 1994; Rivera-Brown & Frontera, 2012). During prolonged efforts, cardiac drift occurs, i.e. HR increases despite constant workload, due to rising core temperature, sympathetic activity, dehydration, and reduced blood volume (Coyle & González-Alonso, 2001). The recovery of HR (HRR) and HR variability (HRV) depends more on the intensity than duration of exercise (Seiler et al., 2007). Further, ventilation increases linearly with $\dot{V}O_2$ up to the second ventilatory threshold, then rises disproportionately at higher intensities due to increased carbon dioxide (CO_2) from buffering lactic acid (Brooks et al., 2005; Rivera-Brown & Frontera, 2012). $\dot{V}O_2$ stabilizes at intensities below the first metabolic threshold. Above this point, a slow component of $\dot{V}O_2$ delays or prevents steady state and carbohydrate oxidation increases as indicated by a rising respiratory exchange ratio (RER). Stress hormones such as catecholamines, cortisol, and adrenocorticotropic hormone rise in proportion to exercise intensity, supporting substrate mobilization (Lambert, 2016). Blood lactate remains near baseline during LIT, increases moderately during MIT, and prevents steady state during HIIT (Faude et al., 2009). Additionally, exercise, and especially HIIT, can lead to muscle fiber damage, inducing increasing creatine kinase concentrations (CK) in the blood (Paulsen et al., 2012). Metabolic markers such as lactate and $\dot{V}O_2$ generally return to baseline within 30 minutes with active recovery accelerating lactate clearance (Menzies et al., 2010), but excess post-exercise $\dot{V}O_2$ or CK can persist for hours, increasing with exercise intensity (Borsheim & Bahr, 2003). Submaximal HR may even improve for several days post-exercise due to acute plasma volume expansion (Buchheit et al., 2009; Stanley et al., 2013). Besides metabolic markers, neuromechanical performance can be acutely impaired following exercise, depending on the intensity as well (Cipryan et al., 2017).

In addition, changes in blood lactate concentrations and HR are highly correlated with changes in RPE (Borg et al., 1987). Hence, the perceived effort or athlete-reported measures are typically assessed via scales such as the RPE scales (0-10 or 6-20) (Borg & Noble, 1974) or the Short Recovery and Stress Scale (SRSS) consisting of four dimensions each regarding recovery (physical performance capability, mental performance capability, emotional balance, and overall recovery) and stress (muscular stress, lack of activation, negative emotional state, and overall stress) (Kölling et al., 2020). Perceived exertion typically increases during endurance exercise, independent of whether power output or running speed is maintained even at relatively low intensities (Steed et al., 1994). Following prolonged or high-intensity exercise, perceptual markers commonly remain elevated for more than 24 hours, especially after long-distance running (Siegl et al., 2017).

In sum, acute responses across multiple domains, such as cardiorespiratory (e.g., $\dot{V}O_2$ kinetics, HRmax), biochemical (e.g., CK, blood lactate concentration), autonomic regulation (e.g., HRR), and athlete-reported outcomes (e.g., RPE, SRSS), can provide valuable information for evaluating training intensities (Buchheit, Hader, et al., 2012; Cipryan et al., 2017; Seiler & Sylta, 2017).

Chronic Adaptations

Consistent endurance training triggers a wide range of long-term modifications in cardiovascular, pulmonary, muscular, metabolic, and neuromuscular systems, enabling more efficient oxygen delivery, energy use, and resistance to fatigue. These changes are generally classified as central, enhancing oxygen transport, and peripheral, improving oxygen use, adaptations (Rosenblat et al., 2022).

Regarding central adaptations, of the earliest changes, occurring within a few weeks of training, is an increase in plasma volume, supporting a larger stroke volume (Goodman et al., 2005; Rivera-Brown & Frontera, 2012). Over time, the left ventricle undergoes hypertrophy and chamber enlargement, allowing greater ejection volume and maximal cardiac output (Mihl et al., 2008), important central adaptations determining $\dot{V}O_2$max (Bassett & Howley, 2000). Resting and submaximal HR drop due to enhanced parasympathetic tone, and blood pressure is reduced (Carter et al., 2003; Pescatello et al., 2004). Total hemoglobin and red blood cell mass are most important in delivering oxygen to the muscle (Ward, 2006). In this regard, plasma expansion may dilute hemoglobin concentration, but oxygen-carrying capacity is maintained or improved following training, in turn enhancing $\dot{V}O_2$max and RE (Montero et al., 2015).

One of the most important peripheral adaptations is increasing capillarization, i.e., angiogenesis, with up to a 20% rise in capillary-to-fiber ratio within weeks (Liu et al., 2022; Murias et al., 2011). Additionally, mitochondria proliferate and enlarge, and oxidative enzymes increase following training (Lundby & Jacobs, 2016; Murias et al., 2011), raising oxidative capacity. These changes support higher oxygen extraction, lower lactate accumulation, and greater fat oxidation at given intensities which in turn improve metabolic thresholds and $\dot{V}O_2$max (Burgess & Lambert, 2010; Lambert, 2016).

Endurance training also affects neuromuscular adaptations and long-term endurance training favors a high proportion of slow-twitch fibers, which resist fatigue (Allen et al., 2008; Wilson et al., 2012). Neuromuscular adaptations to endurance training include delayed recruitment of fast-twitch fibers, greater coordination efficiency, and a shift of fiber types

(Ronnestad & Mujika, 2014; Wilson et al., 2012). These changes enhance RE and allow higher fractional utilization of $\dot{V}O_2max$ to be sustained (Swinnen et al., 2024).

While high-volume and high-intensity training can influence specific adaptations, they also yield overlapping benefits, likely through distinct molecular pathways. Therefore, elite endurance athletes generally integrate different training formats depending on macro- and meso-training cycles (Rosenblat et al., 2025; Sandbakk et al., 2025; Seiler, 2010). LIT mainly promotes peripheral changes such as capillary proliferation (i.e., angiogenesis) (Wahl et al., 2014) and mitochondrial enzyme activity (Lundby & Jacobs, 2016), while HIIT stimulates central adaptations like increased stroke volume (Laursen & Jenkins, 2002), mitochondrial biogenesis (Lundby & Jacobs, 2016), and improved oxidative capacity in type II fibers (Gibala & McGee, 2008). HIIT also elevates muscle buffering capacity (Edge et al., 2006), valuable in shorter events. SIT primarily influences peripheral changes such as angiogenesis besides neuromuscular adaptations (Rosenblat et al., 2022).

To sum up, HIIT bears high cardiovascular and metabolic demands and is therefore considered most effective for increasing $\dot{V}O_2max$ (de Oliveira-Nunes et al., 2021; Ma et al., 2023). While some studies found similar improvements in $\dot{V}O_2max$ following SIT (de Oliveira-Nunes et al., 2021) by enhancing capillary density (Rosenblat et al., 2022), subsequent studies did not confirm these results (Helgerud et al., 2023; Hov et al., 2023). HIIT and especially SIT enhance neuromuscular capabilities such as intermuscular coordination and fast-twitch fiber recruitment (Benitez-Flores et al., 2021; Nummela et al., 2006). The anaerobic threshold can be enhanced following HIIT by increased buffering capacity and oxidative capacity of slow-twitch fibers (Gibala & McGee, 2008); however, LIT and MIT seem to be more effective in improving lactate threshold and shifting to a higher fractional utilization of $\dot{V}O_2max$ by enhancing fat oxidation, reducing lactate production at a given workload, and increasing lactate clearance (Esteve-Lanao et al., 2007). Figure 2.4 provides a simple overview of acute responses and chronic adaptations to endurance training, leading to enhancements in determinant factors of endurance performance. Since the directions of change can differ depending on the exercise and changes in other outcomes, the adaptations are not marked with any direction, while leading to an increase in determinants of endurance performance.

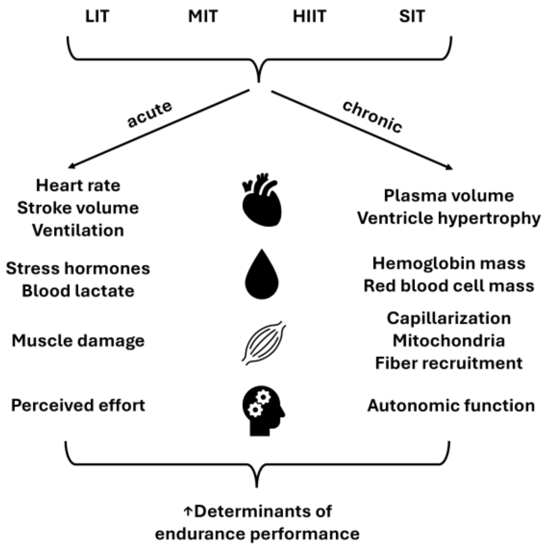

Figure 2.4: Simple overview of acute responses and chronic adaptations leading to enhancements in determinant factors of endurance performance. LIT – low intensity training; MIT – moderate intensity trainings; HIIT – high-intensity interval training; SIT – sprint interval training.

Adaptations to endurance training are often studied with groups of athletes of a similar training background or fitness, where methodological factors such as type, volume, and intensity of exercise play a large role in the magnitude of training adaptations (Meyler et al., 2021). However, it is repeatedly evident that athletes respond differently to the same stimulus depending on for example sex, age, genetics, or fitness (Bouchard & Rankinen, 2001; Pickering & Kiely, 2019). Therefore, the following subchapter (Chapter 2.3) discusses the underlying reasons for individual responses to endurance training and explores profiling approaches aiming to explain these differences.

2.3 Individualization in Running-based Sports

Endurance training interventions often follow structured programs that are adjusted to an athlete's training background, either by altering total training volume or varying intensity (Meyler et al., 2021). Individualization can also be achieved by setting intensities according to personal physiological thresholds rather than prescribing training based on maximum physiological anchors (Byrd et al., 2019; Meyler et al., 2021). Moreover, recent research on tailoring supramaximal HIIT (i.e., intensities above MAS) using ASR suggests that prescribing sessions based on two maximal performance benchmarks, rather than MAS alone, may reduce inter-individual variability in responses, pointing towards further individualization of HIIT programming (Dai & Xie, 2023). Despite such standardization, performance and physiological responses can vary widely, and the magnitude of change may vary across different variables (Vollaard et al., 2009), reflecting a complex interplay of biological and contextual influences.

2.3.1 Acute and Chronic Individual Responses

Acute responses to training can differ depending on baseline fitness, age, sex, and competitive status (Thurlow et al., 2023). For example, recreational athletes display higher lactate concentrations than elite athletes during low-intensity training, reflecting lower metabolic efficiency (Nuuttila et al., 2021). Age-related changes in cardiovascular and muscular plasticity influence recovery dynamics and training tolerance, with higher markers of muscle damage (CK) and lower HRV for older athletes compared to younger athletes (Klatt et al., 2021). Sex-based differences in hormones, substrate utilization, and muscle characteristics further shape acute demands (Dent et al., 2015; Thurlow et al., 2023). Muscle fiber composition also affects acute workload perception and fatigue. Athletes with a higher proportion of fast-twitch fibers showed higher markers of fatigue, e.g., higher lactate concentrations and decreased peak torque during maximal voluntary contractions, after three repeated Wingate tests compared to athletes with a higher proportion of slow-twitch fibers (Lievens et al., 2020).

Long-term adaptations are similarly heterogeneous as acute responses. In sedentary men, six weeks of LIT have been shown to elicit changes in $\dot{V}O_2max$ ranging from a slight decline to over 30% improvement (Vollaard et al., 2009). Among recreational runners, changes of peak incremental treadmill speed (v_{peak}) after 9 weeks of training have ranged from no improvements to 10% of improvement following HIIT and from slight decrements to improvements of 4% following LIT (Vesterinen et al., 2016). These findings illustrate that some individuals adapt robustly (i.e., high-responders), while others, often termed as low-responders, show limited change despite following identical, standardized training (Pickering & Kiely, 2019). For example, training type can influence the prevalence of low responders. LIT seems to lead to more positive adaptations, i.e. high-responders, regarding $\dot{V}O_2max$ in recreational runners than HIIT (Düking et al., 2020). Similarly, SIT shows heterogeneous response rates depending on the protocol applied. When work-to-rest ratios were matched, the incidence of response in $\dot{V}O_2max$ was comparable across SIT protocols, while the response of performance-related outcomes differed. Longer sprint and rest durations showed more positive responses for 5,000-m running performance, whereas shorter bouts favored improvements in 30-s sprint efforts (Schulhauser et al., 2021). Those results show that adaptations seem to be parameter-specific: a limited change in $\dot{V}O_2max$ does not necessarily mean an athlete does not improve in other areas, such as for example lactate thresholds or RE. Although some of this variability can be attributed to measurement error and natural biological fluctuations, it also represents genuine individual differences in training responsiveness (Mann et al., 2014). Moreover, genetics account for a significant portion of this variability. The HERITAGE Family Study estimated that 47% of the trainability of $\dot{V}O_2max$ is heritable (Bouchard et al., 1999). In addition, RE has also been linked strongly to genetic predisposition (Barnes & Kilding, 2015a; He et al., 2007). However, non-genetic factors, such as fitness, recovery status, or nutrition also play key roles in the responsiveness to training (Maturana et al., 2021).

In summary, interindividual differences in training responses arise from the interaction of genetic, physiological, and contextual factors (Bouchard et al., 1999; Mann et al., 2014; Maturana et al., 2021). Importantly, non-responsiveness is rarely absolute and could be addressed through program adjustment (Düking et al., 2020). Moreover, profiling could play an important role in explaining individual acute responses and adaptations to training. The role of athlete profiling for individualizing training and optimize adaptations will be discussed in the following subchapter (*Chapter 2.3.2*).

2.3.2 The Role of Profiling for Individualization

Profiling refers to the systematic assessment of athletes' physical characteristics in order to for example monitor adaptations, individualize training prescription, and support talent identification (Weakley et al., 2024). Regarding talent identification, a recent study confirmed that if the muscle fiber typology of athletes matches the track-and-field discipline they trained since youth, e.g., large proportion of fast-twitch fibers as a sprinter, they will most likely be successful at senior level (Vandecauter et al., 2025). Despite novel strategies using magnet resonance spectroscopy, the assessment of muscle fiber typology is still costly and requires highly-skilled staff. Therefore, traditional diagnostics to assess athletes' physical characteristics are still very common. In endurance sports, testing of athletes has traditionally relied on physiological assessments of parameters such as $\dot{V}O_2max$ and lactate thresholds to characterize aerobic fitness (Hollmann, 2006). Since $\dot{V}O_2max$ alone is a poor predictor of running performance among athletes with similar fitness level and especially elite athletes, as described in *Chapter 2.2.1* (Conley & Krahenbuhl, 1980), the combined consideration of markers reflecting different physical capabilities aims to provide a more holistic view of athletes' strengths and weaknesses. In this regard, both aerobic capacity ($\dot{V}O_2max$) and anaerobic power ($\dot{c}Lamax$) can be considered as physiological profiling, which originally stems from metabolic simulations (Heck et al., 2003). Although $\dot{V}O_2max$ has traditionally been emphasized in endurance sports, recent research highlights the value of $\dot{c}Lamax$ for understanding sprint and middle-distance performance, as well as for modestly improving predictions of longer-distance outcomes (Quittmann et al., 2020; Quittmann et al., 2023). Assessing both parameters together allows for more comprehensive metabolic or physiological profiling and capturing the interaction between aerobic and anaerobic energy systems. The underlying metabolic simulation models suggests that an increase in $\dot{V}O_2max$ or a decrease in $\dot{c}Lamax$ might increase the performance at the LT2 (Mader & Heck, 1994; Wackerhage et al., 2022). While these simulation models are currently under debate, it is assumed that athletes whose performance depends predominantly on glycolytic capacity, such as sprinters or certain team sport players depending on position, benefit from a higher ċLamax, whereas those relying primarily on oxidative metabolism perform better with a lower ċLamax (Quittmann et al., 2023).

More recently, locomotor profiling, referring to the ASR concept, has gained prominence (Sandford et al., 2021). The ASR reflects the speed difference between MSS and MAS, hence incorporating neuro-mechanical, coordinative and glycolytic capabilities (related to MSS) as well as oxidative capacity and aerobic performance (related to MAS) (Blondel et al., 2001; Sandford et al., 2021). Although different laboratory and field tests exist to assess the ASR, i.e. MAS and MSS, and the validity and reliability of those tests is not yet clarified, it is suggested that the ASR represents a simple and accessible concept linking physiological and mechanical determinants of performance for profiling athletes (Buchheit & Laursen, 2013a, 2013b; Sandford, Allen, et al., 2019; Sandford, Kilding, et al., 2019). It has also been shown that performance differences can be explained more effectively by combining metabolic and mechanical-coordinative parameters using the ASR rather than by MAS alone, which is limited to metabolic capacity (Blondel et al., 2001; Buchheit, Hader, et al., 2012). Further, it is suggested to categorize athletes into endurance (low ASR due to high MAS), speed (high ASR due to high MSS), or hybrid types (moderate ASR due to moderate MAS and MSS) using the ASR (Sandford et al., 2021) or the speed reserve ratio (SRR) which reflects the quotient of MSS and MSS (Sandford, Allen, et al., 2019). Figure 2.5 displays two examples of different locomotor profiles, i.e., an endurance type (athlete A) and a speed type (athlete B).

Both ASR and SRR must be considered in relation to MAS and MSS. While ASR captures the absolute difference between maximal sprinting and aerobic speed, it can be artificially inflated in athletes with a low MAS, giving the impression of a large reserve and hence being categorized as speed type despite limited fitness. SRR, by normalizing these capacities, addresses this issue but introduces potential ratio bias. Appropriate interpretation therefore requires certain statistical conditions: the regression of MSS and MAS should intercept at zero, the relationship between MAS and MSS should be linear, scaling of SRR should preserve distributional properties, and MAS should not correlate with SRR to avoid confounding their relationship (Van Hooren et al., 2023). Despite these caveats, both metrics have practical value. ASR, in particular, has become a common basis for prescribing HIIT, where it has been shown to produce more uniform acute responses in runners compared to MAS-based HIIT (Collison et al., 2022; Julio et al., 2020) as well as more consistent long-term adaptations than prescriptions based solely on MAS (Dai & Xie, 2023; Wang & Ye, 2024). It has further been proposed that ASR, together with its components MAS and MSS, may serve as a useful predictor of individual tolerance to HIIT. Athletes with lower MAS who utilize a greater proportion of their ASR during repeated sprinting exhibit higher post-exercise blood lactate concentrations and a greater percentage of

$\dot{V}O_2max$ during HIIT (Buchheit, Hader, et al., 2012). Moreover, athletes with a higher ASR showed slower HRR kinetics than those with a lower ASR (Del Rosso et al., 2017). Interestingly and contrary, when comparing athletes from sprint and endurance backgrounds, no differences were observed in acute responses to short- versus long-format HIIT prescribed relative to MAS with respect to cardiac autonomic regulation, inflammation, or muscle damage (Cipryan et al., 2017). However, those athletes were categorized based on their sport discipline and not based on ASR. Similarly, athlete-reported outcomes, such as RPE, appear unaffected by locomotor profile variables (ASR, MAS, MSS) (Julio et al., 2020) or by athlete type (endurance vs. sprint) in response to either HIIT or repeated sprinting (Cipryan et al., 2017). This suggests that ASR might be an accurate predictor of acute responses to intense exercise depending on the outcome variable and type of exercise.

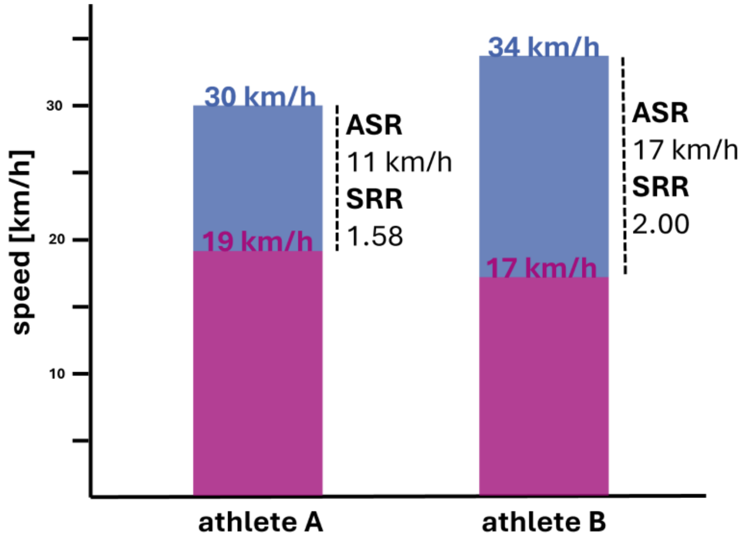

Figure 2.5: Example of two different athletes. Athlete A represents an endurance type and athlete B a speed type. ASR – anaerobic speed reserve; SRR – speed reserve ratio.

Similarly to acute responses, chronic adaptations to training can vary between athletes as discussed in *Chapter 2.3.1*. Locomotor profiling is therefore suggested by Sandford et al. (2021) as a framework to explain differences in training adaptations and to guide individualized program design. This individualized approach aims to consider that athletes with endurance-, hybrid-, or speed-oriented profiles require different training stimuli to optimize adaptation of endurance performance and minimize the risk of maladaptation while maintaining the joy of exercise. Endurance profiles typically exhibit a greater tolerance to continuous, higher-volume training and long-interval HIIT formats, which aligns with their aerobic capacity and fatigue resistance based on a high proportion of more fatigue resistant slow-twitch fibers (Bellinger et al., 2020). These athletes can often sustain double-day sessions and handle higher training loads with relatively low risk of maladaptation (Seiler, 2010). In contrast, applying the same volume-heavy approach to speed-oriented athletes risks excessive fatigue, overreaching, or impaired adaptation (Bellinger et al., 2020). This is partly due to their reliance on fast-twitch muscle fibers, which, when repeatedly recruited under glycogen-depleted or continuous low-intensity conditions, can lead to disproportionate reliance on anaerobic metabolism, elevated $\dot{V}O_2$ slow components, and an inability to sustain steady-state exercise (Krustrup et al., 2004; Poole et al., 2016; Sandford et al., 2021). Therefore, for speed types, aerobic conditioning and fatigue resistance can instead be achieved through targeted recruitment and adaptation of fast-twitch fibers as suggested by short-interval HIIT or SIT (Buchheit & Laursen, 2013b; Henneman, 1985; Sandford et al., 2021). Such formats enable substantial time near $\dot{V}O_2max$ while minimizing lactate accumulation, thereby promoting aerobic adaptations without overwhelming glycolytic contribution (Buchheit & Laursen, 2013b; Sandford et al., 2021). Therefore, SIT is assumed to be particularly suited to speed-profile athletes, as their muscle physiology and metabolic characteristics allow them to tolerate high-intensity efforts while still eliciting meaningful aerobic adaptations through fiber-specific and peripheral mechanisms (Buchheit & Laursen, 2013b; Parkhouse et al., 1985; van der Zwaard et al., 2018). This evidence suggests that neither long or short HIIT is universally optimal for improving endurance performance; rather, the appropriate choice depends on the athlete's locomotor profile (Sandford et al., 2021).

In summary, profiling integrates physical characteristics aiming to improve individualized testing and training of endurance performance. Alongside physiological profiling using $\dot{V}O_2max$ and $\dot{c}Lamax$, the ASR has emerged as a practical tool to distinguish endurance, speed, and hybrid types. Evidence suggests that endurance profiles adapt best to higher volumes and long intervals, whereas speed profiles benefit more from short-interval or sprint interval training (Sandford et al., 2021), highlighting that the effectiveness of training formats might depend on locomotor profile rather than a "one-size fits all" approach.

2.4 Research Gap

Based on the theoretical background of this thesis (Chapters 2.2 and 2.3), several research gaps remain in the field of individualized testing and training using profiling. In running-based sports, endurance performance is determined by metabolic, mechanical, and neuromuscular factors (Hallam et al., 2022; Jones, 2023). Instead of focusing on isolated markers, profiling approaches that combine multiple characteristics can improve training individualization, adaptation monitoring, and talent identification (Weakley et al., 2024). As previously discussed (Chapter 2.3), different approaches for profiling exist: physiological profiling, using $\dot{V}O_2max$ and $\dot{c}Lamax$, provides valuable insights into aerobic capacity and anaerobic power; Locomotor profiling based on ASR and its subcomponents offers a different lens by categorizing athletes into endurance, hybrid, or speed types based on physiological, neuromuscular, and mechanical markers. Both approaches seem promising for evaluation of performance and training prescription (Hallam et al., 2022; Lundby et al., 2017; Sandford et al., 2021), yet their relationship remains unexplored. In particular, it is not clear how well these approaches align or differ across sprint and endurance disciplines. Such insights would be crucial to determine whether the two methods can be applied complementarily.

Moreover, locomotor profiling has become an increasingly popular approach to monitor adaptations and individualize training, yet its usefulness ultimately depends on the accuracy of the underlying measurements of MAS and MSS. Since both profiling athletes and the prescription of training based on the ASR rely on valid and reliable testing of MAS and MSS, it is essential to ensure that observed changes reflect true adaptations rather than measurement error caused by technological or biological sources or intraindividual variance (Simperingham et al., 2016). Previous reviews have addressed factors influencing sprint testing such as surface, footwear, or environmental conditions (Haugen & Buchheit, 2016), as well as aerobic fitness tests such as to estimate $\dot{V}O_2max$, often focusing on a single sport (Bok & Foster, 2021). However, several definitions of MAS and field tests such as time trials or shuttle runs are used in research and practice, although their validity and reliability seem doubtful. Similarly, different methods to assess MSS have shown to yield different results. Yet, no overview currently exists that systematically evaluates the validity and reliability of MAS and MSS testing methods in running-based sports. This leaves researchers and practitioners with little guidance on which protocols to choose and how to interpret changes in performance with confidence. Moreover, the assessment of maximal markers such as maximal aerobic performance, as assessed for example via peak speed in an incremental running test (v_{peak}), requires athletes to exercise to exhaustion, which may be impractical under high training loads or congested competition schedules (Saunders et al., 2010; Stratton et al., 2009). Consequently, identifying submaximal predictors would provide a useful alternative for performance monitoring and training guidance in applied settings. Overall, knowing the validity and reliability of methods to assess the locomotor profile, i.e., MAS and MSS, which can be easily integrated into testing routines, might enhance both research as well as practice by simplifying testing methods while maintaining standardization.

As acute responses or chronic adaptations to training vary between athletes, profiling, and especially locomotor profiling, might be useful in explaining those differences and improve training prescription. Previous research suggests that the ASR may better predict tolerance to high-intensity exercise than MAS alone (Buchheit, Hader, et al., 2012), although findings remain inconsistent and sometimes contradictory. While some studies have linked a lower ASR to lower blood lactate accumulation and faster $\dot{V}O_2$ kinetics or HRR (Buchheit, Hader, et al., 2012; Del Rosso et al., 2017), no effect of locomotor profile (i.e., ASR) on acute outcomes such as RPE, inflammation, or CK was previously found (Buchheit, Hader, et al., 2012; Cipryan et al., 2017). Consequently, further research is needed to clarify how ASR and its components (MAS, MSS) relate to acute physiological, biochemical, neuromuscular, and perceptual responses to HIIT in order to provide guidance for tailoring training programs to individual needs and avoid possible overload. Regarding long-term conditioning and improving endurance performance, it was previously suggested that locomotor profiling can help in choosing the right training stimulus (Sandford et al., 2021). While endurance-oriented athletes appear to respond best to long format HIIT and higher training volumes, and speed-oriented athletes might benefit from short format HIIT or SIT (Sandford et al., 2021), these assumptions are largely based on conceptual assumptions rather than robust experimental data and the moderating role of locomotor profiles in this context has not yet been examined.

Taken together, several research gaps emerge. First, the connection between physiological and locomotor profiling and the value of these approaches for differentiating between runners has not yet been clarified. Second, there is a lack of systematic evaluation of the validity and reliability of MAS and MSS testing protocols as well as submaximal prediction of maximal aerobic performance in running-based sports. Third, the role of locomotor profiles in moderating acute responses and long-term adaptations to different HIIT formats remains underexplored. Addressing these issues will be essential to strengthen the scientific foundations of profiling and to optimize individualized training prescription.

In summary, Chapter 2 outlined the theoretical background of this thesis by discussing the key determinants of endurance performance and highlighting the potential of athlete profiling as a tool for individualized testing and training. As noted, several research questions in this area remain unresolved and will be addressed in the subsequent chapters. Accordingly, Chapter 3 presents the specific aims and scope of this thesis.

3 Aims and Scope of this Thesis

This chapter connects the theoretical background discussed in Chapter 2 with the studies (Chapters 4–6) presented in this thesis. Despite the growing interest in athlete profiling as a tool for individualizing training, several important questions remain unsolved, leading to the three main aims of this thesis.

As outlined in Chapter 2.4, the main aims are based on three identified research gaps, summarized again in the following: First, the relationship between physiological profiling (e.g., $\dot{V}O_2max$, $\dot{c}Lamax$) and locomotor profiling (e.g., ASR and its subcomponents MAS and MSS) has not yet been clarified. While both methods provide valuable but distinct perspectives on endurance and sprint performance, it is not known to what extent they align with each other, or reveal differences across running disciplines. Second, although MAS and MSS represent key measures for locomotor profiling and high-intensity training prescription, no evaluation and systematic overview of the validity and reliability of testing methods exist in running-based sports. This limits practitioners' ability to interpret observed changes with confidence. Third, the role of locomotor profiles in evaluating acute responses and chronic adaptations to different HIIT formats remains largely unexplored. Understanding whether endurance-, hybrid-, and speed-type athletes respond differently to specific training stimuli is crucial to move beyond conceptual reasoning toward evidence-based recommendations for practice.

Accordingly, this thesis pursues three main aims:

A. To investigate the value and relationship between physiological and locomotor profiling across running disciplines.
B. To evaluate and systematically review the validity and reliability of tests to assess MAS and MSS in running-based sports.
C. To examine the role of locomotor profiles in explaining acute responses and chronic adaptations to different HIIT formats.

These aims were addressed through a systematic review (Paper III) and five original studies, including two cross-sectional (Papers I and II), one retrospective (Paper IV), and two intervention studies (acute intervention: Paper V; longitudinal intervention: Paper VI), published (or under review: Papers V and VI) in international peer-reviewed scientific journals. A schematic overview of the included papers and how they relate to the outlined aims is presented in Figure 3.1.

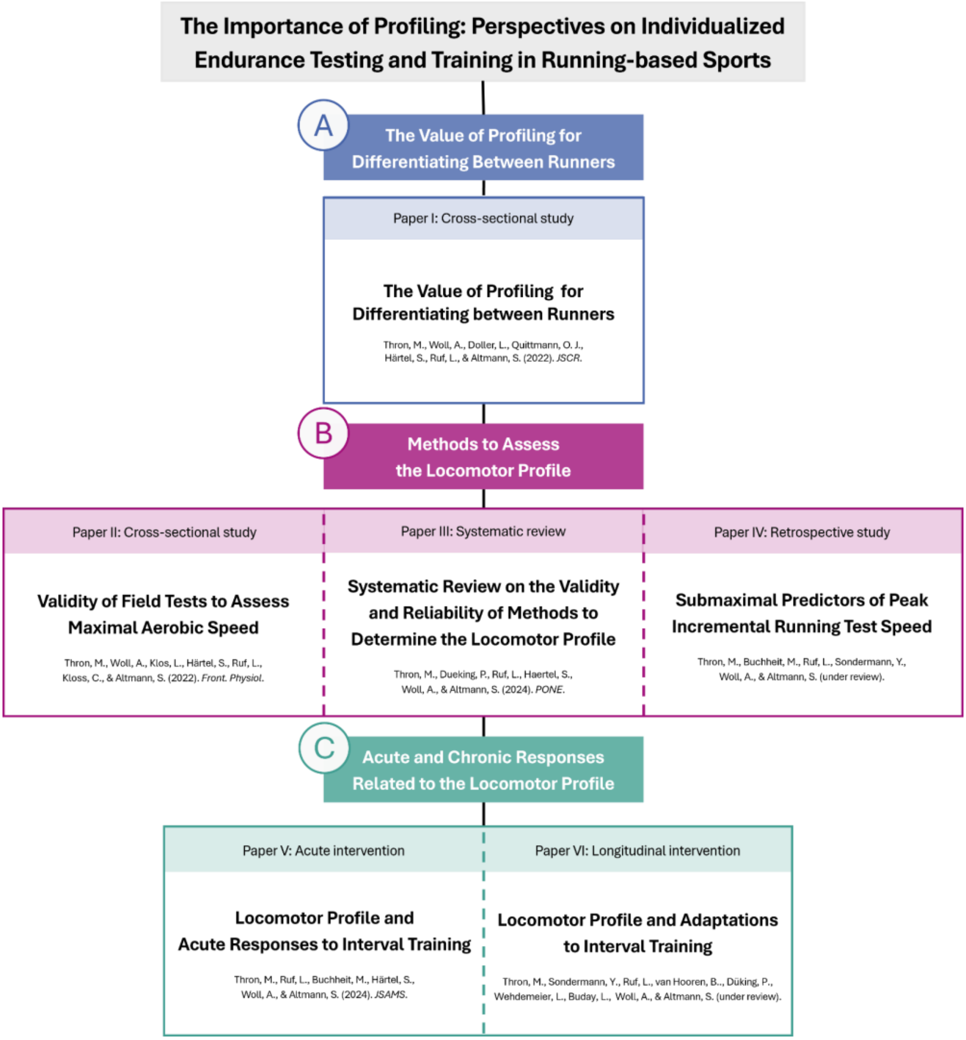

Figure 3.1: Overview of the studies included in this thesis structured by its three main aims: (A) The value of profiling for differentiating between runners (Paper I), (B) Methods to assess the locomotor profile (Papers II – IV), (C) Acute responses and chronic adaptations related to the locomotor profile (Papers V + VI).

Overall, this thesis seeks to advance the understanding of profiling, particularly locomotor profiling, as an approach for individualizing endurance testing and training in running-based sports. The findings are aiming to offer a scientific foundation for applying locomotor profiling in areas such as performance monitoring or the evaluation of training. The following subchapters (Chapters 3.1–3.3) will outline the specific aims of each paper and describe the general methodological approaches used to address them.

3.1 The Value of Profiling for Differentiating between Runners (Paper I)

As summarized in Chapter 2.2, endurance performance in running-based sports depends on mechanical, neuromuscular, and metabolic factors (Hallam et al., 2022; Jones, 2023). Besides considering single markers as determinants of endurance performance, profiling as a combined evaluation of athletes' physical characteristics might improve for example individualization of training prescription, monitoring of adaptations, and support talent identification (Weakley et al., 2024). As depicted in Chapter 2.3, $\dot{V}O_2max$ and $\dot{c}Lamax$ together may allow physiological profiling by capturing the interaction of oxidative and glycolytic ATP resynthesis, with potential implications for performance optimization through targeted training (Wackerhage et al., 2022). An alternative, locomotor approach uses the ASR to classify athletes according to their endurance, hybrid, or speed-type profiles (Hallam et al., 2022; Sandford, Allen, et al., 2019). Besides physiological capabilities, this method integrates mechanical and neuromuscular capabilities.

Although both approaches, physiological and locomotor profiling, appear promising for evaluating performance (Hallam et al., 2022; Quittmann et al., 2023), their relationship has not been systematically explored. In particular, it is unclear how these methods relate across different running disciplines. Therefore, Paper I aims to compare physiological and locomotor profiles of adolescent and young adult male and female sprinters, 400-m runners, and middle-distance runners, and to examine the relationships between these two approaches. The findings of this study could be of interest for assessing strengths and weaknesses (e.g., for talent identification) or training prescription in these disciplines.

In this regard, the cross-sectional study employed an observational design to compare subgroups (sprinters, 400-m runners, and middle-distance runners) and examine relationships between profiling parameters. Youth, male and female highly trained runners completed two 100-m sprints to assess MSS, while $\dot{c}Lamax$ was derived using lactate kinetics. Additionally, participants performed an incremental cardiopulmonary exercise test (CPET) on a treadmill to determine MAS and $\dot{V}O_2max$. Additionally, World Athletics (WA) scores were recorded based on each athlete's personal best in their primary discipline.

Comparisons between groups were assessed via analyses of variance (ANOVA) and equivalence testing.

3.2 Methods to Assess the Locomotor Profile (Anaerobic Speed Reserve) (Papers II–IV)

Given that the findings of Paper I showed strong similarities between locomotor and physiological profiles of sprinters and middle-distance runners, the following studies focused on locomotor profiling based on the ASR and its components. Because profiling athletes as well as prescribing HIIT using the ASR depends on accurate assessments of MAS and MSS, it is essential to ensure that observed changes reflect true adaptations rather than measurement error, whether systematic or random, arising from technological, biological, or intraindividual sources (Simperingham et al., 2016). Therefore, the choice of measures requires careful consideration. Moreover, identifying potential submaximal predictors of v_{peak} as a proxy or maximal aerobic power (e.g., MAS) might improve regular performance assessments and evaluations during periods of high loads (Buchheit, Simpson, et al., 2012). Consequently, in the following subchapters, the aims of Papers II–IV as well as the general methods will be outlined.

3.2.1 Validity of Field Tests to Assess Maximal Aerobic Speed (Paper II)

Since MAS represents the lower benchmark of ASR and serves for evaluation of endurance performance and the prescription of HIIT in running-based sports such as soccer, precise assessments are inevitable. CPET on a treadmill is used as a gold standard method to assess MAS. Nevertheless, different treadmill protocols and definitions of MAS exist, which provide different results of MAS (Berthoin et al., 1996; Billat et al., 1996; Riboli et al., 2021). In addition, field tests such as the Université de Montréal Track Test (UMTT) or fixed-distance time trials (e.g., 1,500-m TT) are often used to estimate MAS, yet findings on their validity remain inconsistent (Darendeli et al., 2021; Lacour et al., 1991; Sandford, Rogers, et al., 2019). To address this gap, Paper II aims to compare two definitions of MAS derived from treadmill CPET, and to examine the convergent validity of the UMTT and a 1,500-m TT against MAS assessed via CPET in soccer players. Thereby, this study aims to contribute to refining MAS assessment and to evaluating whether the UMTT or 1,500-m TT can serve as practical substitutes for laboratory testing.

In this cross-sectional study, trained male soccer players performed an incremental CPET on a treadmill to assess $\dot{V}O_2$ kinetics and thereby MAS by two different definitions. Moreover, players performed an incremental running test (UMTT) and a 1,500-m TT on an outdoor running track where estimates of MAS were assessed as peak speed and average speed, respectively. The validity of MAS estimates was assessed using ANOVA as well as limits of agreement and correlation analyses.

3.2.2 Systematic Review on the Validity and Reliability of Methods to Determine the Locomotor Profile (Paper III)

Besides *Paper II* providing results regarding an overestimation of CPET derived MAS by field tests such as the UMTT and a 1,500-m TT, different laboratory and field tests to assess or estimate MAS are widely used in research and practice (Buchheit, 2010; Sandford, Rogers, et al., 2019; Sangan et al., 2021). Regarding MSS, linear sprint tests of 20–50 m with radar or laser are regarded as the gold standard methods, although timing gates as well as global and local positioning systems (GPS, LPS) are also frequently used, particularly in soccer where match and training data are readily available (Beato et al., 2018; Djaoui et al., 2017; Lacome et al., 2019; Ortiz et al., 2018; Simperingham et al., 2019). Because both HIIT prescription based on the ASR and locomotor profiling depend on valid and reliable measurements of MAS and MSS, careful selection of testing protocols is essential to avoid confounding effects from measurement error or individual variability (Simperingham et al., 2016). While previous reviews have addressed factors influencing sprint testing (Haugen & Buchheit, 2016) or aerobic fitness tests to assess $\dot{V}O_2max$ (Bok & Foster, 2021), no systematic overview exists on the validity and reliability of MAS and MSS assessments across running-based sports, e.g., team sports or track and field. Therefore, *Paper III* aims to provide an overview of the existing literature regarding validity and reliability of methods to assess MAS and MAS, to guide researchers and practitioners in selecting appropriate methods for different contexts.

In this systematic review, the literature was screened according to the preferred reporting items for systematic reviews and meta-analyses (PRISMA 2020) (Page et al., 2021). To be included, studies had to meet the patient, intervention, comparator, outcome, and study (PICOS) criteria (Amir-Behghadami & Janati, 2020), and methodological quality was assessed through the consensus-based standards for the selection of health measurement instruments (COSMIN) checklist (Mokkink et al., 2020; Mokkink et al., 2018).

3.2.3 Submaximal Predictors of Peak Incremental Running Test Speed (Paper IV)

When breathing gas data is not available, v_{peak} can serve as a proximate of maximal aerobic performance, albeit typically exceeding MAS by around 3% (Berthoin et al., 1996). Although v_{peak} is a valuable marker, its assessment typically requires athletes to exercise to exhaustion, which may be impractical during phases of dense competition or heavy training, such as a soccer season. In these situations, submaximal indicators like lactate thresholds or HR measures, which are easy to obtain without maximal effort, may provide a practical alternative for monitoring. Accordingly, Paper IV aims to evaluate the potential of such submaximal markers, derived from incremental running tests, to predict v_{peak} in professional soccer players. Establishing reliable submaximal predictors could improve monitoring strategies while preserving the accuracy of performance assessment.

In this retrospective study, youth and adult, male and female soccer players (highly trained) performed one or more incremental running tests to exhaustion, either on a treadmill or a running track. The potential of submaximal markers to predict v_{peak} was evaluated using linear mixed models and k-fold cross-validation. To enhance the practical applicability of the study, an online calculator was developed to allow for an easily accessible, submaximal prediction of v_{peak} based on the identified predictors.

3.3 Acute Responses and Chronic Adaptations Related to the Locomotor Profile (Papers V + VI)

As mentioned in Chapter 2.3, high variability exists in acute responses as well as chronic adaptations to endurance training and especially HIIT, whereby profiling of athletes might provide guidance in explaining individual differences. Paper I demonstrated the value of locomotor profiling for characterizing and distinguishing athletes across different running disciplines, while Papers II–IV evaluated and reviewed valid and reliable methods for assessing the key locomotor variables MAS and MSS. Building on these findings, the subsequent application of the locomotor profile aimed to explore its role in explaining interindividual differences in acute responses and chronic adaptations to training. Given the inconsistent and partly contradictory evidence on whether ASR and its components influence tolerance to high-intensity exercise and recovery, the following Papers V and VI sought to clarify how locomotor profiles relate to acute responses and chronic adaptations to HIIT, and whether they can provide practical guidance for tailoring training prescriptions to different locomotor types.

3.3.1 Locomotor Profile and Acute Responses (Paper V)

HIIT is essential for improving endurance performance in running-based sports, yet athletes show considerable differences in their tolerance to such training (see Chapter 2.3.1) (Cipryan et al., 2017; Lievens et al., 2020). Locomotor profiling, more specifically the ASR and its components MAS and MSS, has been proposed as a framework to explain these differences (Blondel et al., 2001; Buchheit, Hader, et al., 2012). While previous research indicates that ASR-based HIIT prescription may produce more homogeneous adaptations than other approaches (Bok, Gulin, Škegro, et al., 2023), findings on the relationship of the ASR with acute physiological, biochemical, neuromuscular, and athlete-reported responses remain heterogeneous and contradictory (Cipryan et al., 2017; Del Rosso et al., 2017). Given that MAS-based prescription of HIIT remains common practice, it is important to examine how different locomotor profiles influence responses following MAS-based HIIT (2 sets of 20x 15 s at 110% MAS with 15 s passive rest). Therefore, Paper V aims to investigate associations between the ASR and its components with acute cardiorespiratory, biochemical, neuromuscular, and athlete-reported responses to MAS-based short-format HIIT in runners. By clarifying these associations, this work seeks to provide practical insights into optimizing HIIT prescription and reducing the risk of overload.

In this acute intervention study, highly trained, male and female youth runners completed testing across two visits. During the first visit, MSS was determined from two 60-m sprints, followed by a treadmill CPET to assess MAS. At the second visit, athletes performed a short-format HIIT session, while assessing a comprehensive set of measurements regarding acute responses before (biochemical, neuromuscular, cardiac, and athlete-reported measures), during (cardiopulmonary measures), post (biochemical, neuromuscular, cardiac, and athlete-reported fatigue, stress, and recovery measures), and 24-h delayed (athlete-reported fatigue, stress, and recovery measures) to evaluate individual responses to HIIT. The influence of the locomotor profile on the acute responses was determined via correlation analyses.

3.3.2 Locomotor Profile and Adaptations to Interval Training (Paper VI)

Although both HIIT and SIT have been shown to improve $\dot{V}O_2max$ and MAS, findings in trained athletes remain inconsistent, with considerable interindividual variability in performance and adaptation outcomes (see Chapter 2.3.1). This variability suggests that group-based conclusions are not always sufficient and that individual factors may influence the effectiveness of a given training stimulus (Pickering & Kiely, 2019; Williams et al., 2017). In this regard, profiling athletes through MAS, MSS, and their derivatives (ASR, SRR) offers a promising framework for explaining these differences as outlined in Chapter 2.3.2. Moreover, Paper V revealed substantial benefit of knowing athletes' locomotor profiles in explaining acute responses to HIIT, though, the role of locomotor profiles in moderating chronic adaptations to HIIT and SIT has not yet been investigated. Consequently, Paper VI aims to determine locomotor and physiological changes to HIIT (4–6x 4 min at 90–95% MAS with 2 min rest at low intensity) versus SIT (6–8x 20 s all-out sprinting with 3 min rest at low intensity), and whether locomotor profiles moderate these responses in trained male and female runners. Understanding individual responses to training is crucial for optimizing training strategies, hence the study's findings could highlight the applicability of considering individual profiles when selecting training stimuli in performance development.

In this controlled trial (longitudinal intervention study), trained adult runners were stratified by MAS and MSS (and sex-matched) to six weeks of either HIIT or SIT, performed twice weekly. Pre- and post-intervention testing included two 40-m sprints and a treadmill CPET to assess changes in physiological and locomotor markers using linear mixed models. Moreover, moderating effects of the baseline locomotor profile (SRR, ASR, MAS, and MSS) on these changes were assessed.

Overall, the three main aims of this thesis are addressed by a broad variety of study designs and statical methods to deepen the understanding of profiling for individualized endurance testing and training. In the following Chapters 4–6 the included studies are presented.

4 The Value of Profiling for Differentiating between Runners (Paper I)

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4.1 Abstract

Different approaches exist for characterizing athletes, e.g., physiological and locomotor profiling. The aims of this study were to generate and compare physiological and locomotor profiles of male and female runners, and to evaluate relationships between the different approaches. Thirty-four highly trained adolescent and young adult female and male athletes (n=11 sprinters; n=11 400-m runners; n=12 middle-distance runners) performed two 100-m sprints on a running track to determine maximal sprinting speed (MSS) and maximal lactate accumulation rate ($\dot{c}La_{max}$). A cardiopulmonary exercise test (CPET) was performed on a treadmill to determine maximal aerobic speed (MAS) and maximal oxygen uptake ($\dot{V}O_2max$). Anaerobic speed reserve (ASR) was calculated as the difference between MSS and MAS. Group comparisons were conducted with a two-way ANOVA (discipline*sex; $p<0.05$) and Bonferroni posthoc tests and Cohen's d as effect-size. Parameters were correlated by Pearson's correlation coefficients. MAS and $\dot{V}O_2max$ were higher in 400-m and middle-distance runners compared to sprinters ($p\leq0.02$; $-2.24\leq d\leq-1.29$). MSS and $\dot{c}La_{max}$ were higher in sprinters and 400-m runners compared to middle-distance runners ($0.03\leq p\leq0.28$; $0.73\leq d\leq1.23$). ASR was highest in sprinters and lowest in middle-distance runners ($p\leq0.03$; $1.24\leq d\leq2.79$). High correlations were found between ASR and MAS, MSS, and $\dot{c}La_{max}$ ($p<0.01$; $-0.55\leq r\leq0.91$) and between $\dot{c}La_{max}$ and MSS ($p<0.01$; $r=0.74$). Our results indicate that athletes of different sprinting and running disciplines show differing physiological and locomotor profiles and that the parameters of these approaches are related to each other. This can be of interest for assessing strengths and weaknesses (e.g., for talent identification) or training prescription in these disciplines.

4.2 Introduction

Performance in running events relies on mechanical and neuromuscular factors as well as the capabilities of various energy supplying systems (Hallam et al., 2022). Whereas the power of oxidative phosphorylation is quantified by maximal oxygen uptake ($\dot{V}O_2max$), the power of substrate level phosphorylation (glycolysis) can be quantified by maximal rate of lactate accumulation ($\dot{c}$Lamax). $\dot{V}O_2max$ is seen as one of the most important (aerobic) parameters in endurance sports and positively correlates with running distance (Lundby et al., 2017). While the $\dot{c}$Lamax is considered a parameter that can describe anaerobic metabolism, rather few articles have focused on $\dot{c}$Lamax; especially in running (Heck et al., 2003). Previous research developed a reliable field-test to determine $\dot{c}$Lamax in running and found a strong relationship to 100-m sprint performance (Quittmann et al., 2020). Furthermore, $\dot{c}$Lamax allowed "for significant (yet minor) improvements in 5000-m performance prediction in a mixed-sex group" (Quittmann et al., 2023). It is assumed that both parameters ($\dot{V}O_2max$ and $\dot{c}$Lamax) can be used for physiological profiling by simulating the interaction between oxidative and glycolytic ATP resynthesis during exercise (Wackerhage et al., 2022). This approach suggests that an increase in $\dot{V}O_2max$ or a decrease in $\dot{c}$Lamax might increase the performance at the lactate threshold. Adapting the two parameters through targeted training could thus have an impact on performance (Wackerhage et al., 2022).

A locomotor approach for profiling runners is based on the anaerobic speed reserve (ASR) which is defined as the speed range between the maximal aerobic speed (MAS) and maximal sprinting speed (MSS) and can reflect an athlete's tolerance to high-intensity exercise (Sandford et al., 2021). Hence, the ASR enables to assess locomotor profiles through physiological/aerobic (related to MAS) as well as anaerobic, mechanical, and neuromuscular parameters (related to MSS) (Sandford et al., 2021). The speed reserve ratio (SRR) reflects the ratio between MSS and MAS and has recently been used to classify middle-distance runners into subgroups (400 – 800-m athletes, 800-m specialists, 800 – 1500-m athletes) (Hallam et al., 2022; Sandford, Allen, et al., 2019). Furthermore, locomotor profiling based on ASR and its subcomponents might help to categorize athletes into speed types (high ASR and MSS, low MAS), hybrid types (moderate ASR, MSS, and MAS), and endurance types (low ASR and MSS, high MAS). This categorization can be relevant for the assignment to a specific discipline and individualizing the athletes' training prescription, e.g., for high-intensity interval training (Sandford et al., 2021).

Both the physiological and locomotor approaches seem to be promising for profiling athletes and evaluating performance outcomes in running (Hallam et al., 2022; Lundby et al., 2017; Sandford et al., 2021). However, the relationship between these two approaches and the comparison of sprinting and running disciplines as well as between sexes for these approaches have (to our knowledge) not yet been investigated. Therefore, our study aims to compare physiological and locomotor profiles of adolescent and young adult male and female sprinters, 400-m runners, and middle-distance runners and examine relationships between the different approaches.

4.3 Methods

4.3.1 Experimental approach to the problem

An observational study design was used to compare the different subgroups and to assess relationships between the different parameters. After a standardized warm-up, each athlete conducted two 100-m sprints with 30-min rest to assess the MSS (= the fastest sprinting speed out of the two sprints) and $\dot{c}$Lamax (assessed during the first sprint). After a 30-min passive rest, the participants performed a CPET on a treadmill to assess the MAS and $\dot{V}O_2max$. Additionally, World Athletics (WA) scores were documented based on the personal best times in their main discipline.

4.3.2 Subjects

In this study, N=34 adolescent and young adult female (n=15; body mass 59.4±7.3 kg; height 1.69±0.05 m; age 17.9±1.7 years; training 11.5±2.1 hours per week; expertise 8.6±3.5 years of systematic training; see Table 4.1) and male runners (n=19; body mass 73.6±6.7 kg; height 1.82±0.06 m; age 19.2±3.3 years; training 12.2±4.6 hours per week; expertise 7.9±3.9 years of systematic training) were included. Based upon their performance and the expertise in their respective discipline (see Table 1), they were classified as tier three athletes (highly-trained) (McKay et al., 2022). The athletes were recruited based on their performance related to the minimum requirements of the state squad in their discipline which determined the sample size. The participants were categorized as 100–200-m (sprinters; N=11; female n=6), 400-m (400-m runners; N=11; female n=4), and 800–1500-m (middle-distance runners; N=12; female n=5) subgroups based on their self- and their coaches' reported focus during training and competition. Besides anthropometric measures, the participants' expertise in training in their main discipline, hours of training per week, personal best times, and WA scores (Spiriev, 2022) were documented (see Table 1). This study was approved by the local ethics committee according to the Declaration of Helsinki (Approval Number: 22-10). Participants' health was checked and confirmed by the Physical Activity Readiness Questionnaire (Tremblay et al., 2012). The participants and their legal guardians were informed about the procedures and possible risks and agreed to participate by signing a consent form.

Table 4.1: Description of participants

		Mass [kg]	Height [m]	Age [years]	Training [h/week]	Expertise [years]	Personal best time [s]	WA scores
		Mean ± SD						
100 – 200m	♂	77.20 ± 5.84	1.84 ± 0.06	16.60 ± 0.89	11.60 ± 2.07	7.60 ± 3.44	100m: 11.52 ± 0.48 200m: 23.44 ± 1.19	743.40 ± 128.49
	♀	61.33 ± 6.38	1.71 ± 0.05	16.83 ± 1.47	11.00 ± 2.10	8.83 ± 3.19	100m: 12.61 ± 0.40 200m: 25.43 ± 0.76	897.67 ± 55.73
400m	♂	73.90 ± 7.14	1.81 ± 0.06	18.86 ± 3.38	14.14 ± 6.99	7.83 ± 3.59	400m: 51.31 ± 3.98	780.14 ± 222.42
	♀	60.88 ± 10.56	1.69 ± 0.09	19.00 ± 2.16	12.00 ± 1.63	11.5 ± 3.11	400m: 57.42 ± 2.03	926.75 ± 71.47
800 – 1500m	♂	70.71 ± 6.46	1.83 ± 0.06	21.00 ± 3.37	10.57 ± 1.62	8.00 ± 4.86	800m: 113.54 ± 3.19 1500m: 248.03 7.83	925.57 ± 79.64
	♀	55.89 ± 5.38	1.67 ± 0.02	18.00 ± 1.22	11.70 ± 2.73	6.00 ± 2.55	800m: 138.13 ± 10.29 1500m: 270.93 ± 24.02	901.40 ± 98.95

100-200m – sprinters; 400m – 400-m runners; 800-1500m – middle-distance runners; SD – standard deviation; WA – World Athletics.

4.3.3 Procedures

Sprinting

The 100-m sprints were implemented either on an outdoor or indoor Tartan™ track depending on the available location of the athletes. Before the first sprint, the participants rested for 10 min and 20 µl of capillary blood was collected from the right earlobe immediately before the sprint to assess resting lactate (La_{pre}). The athletes started sprinting in a standing position and the velocity was continually recorded with a radar gun (Stalker ATS II; 46.875 Hz; Richardson; USA). The radar gun was placed on a waist-high tripod 2 m behind the start. The data were first processed with the manufacturer's software. Using a custom-made R Studio (Team, 2022) script, speed-time curves were then fitted by a biexponential function (Morin et al., 2006) to calculate MSS and time to reach maximal power (t_{Pmax}) according to Samozino et al. (2016). The time to complete the 100 m (t_{100}) was determined via single beam timing lights with error correction-processing algorithms sampling at 1,000 Hz (Smartspeed Pro, Fusion Sport, Coopers Plains, Australia). Immediately after the first sprint, the participants had to sit down and capillary blood was taken every minute until 10 min after the sprint to assess the maximum of post-exercise lactate concentration (La_{max}). The capillary blood was analyzed using the BIOSEN C-Line lactate analyzer (EKF Diagnostic; Barleben; Germany). The ċLamax was then calculated according to Eq. (1) (Heck et al., 2003; Manunzio et al., 2016).

$$(1)\ \dot{c}Lamax = \frac{La_{max} - La_{pre}}{t_{100} - t_{Pmax}}$$

where La_{max} (mmol/L) = maximal lactate concentration after the exercise; La_{pre} (mmol/L lactate concentration before exercise; t_{100} (s) = duration of exercise, i.e., the 100-m sprint; t_{Pmax} (s) = time to reach maximal power during the sprint.

Cardiopulmonary exercise testing

The CPET on a treadmill (PPSmed 55, PPSmed L70, 4front, or ST 4front; WOODWAY GmbH; Weil am Rhein; Germany) started at 2.22 m/s (8 km/h) with a constant incline of 1% and increased every minute by 0.28 m/s (1 km/h) until subjective exhaustion of the participants (Billat et al., 1996; Sandford, Rogers, et al., 2019). Breath-by-breath ventilatory data were obtained using the Metalyzer 3B or MetaMax 3 spirometer and the appropriate MetaSoft 3 software (Cortex Biophysik GmbH; Leipzig; Germany). A 15-s moving average filter was used for further analysis (Vogler et al., 2010). Gas sensors were calibrated using gases of known concentrations (15% O_2, 5% CO_2), and the turbine volume transducer was calibrated using a 3-L syringe (Cortex Biophysik GmbH; Leipzig; Germany). This procedure was previously suggested by Vogler et al. (2010). The $\dot{V}O_2$ data were first examined for a plateau which is defined as a lower increase in $\dot{V}O_2$ than

150 mL/min in at least the last minute of exercise (Thron, Woll, et al., 2022). The $\dot{V}O_2max$ was defined as the highest 30-s-interval of $\dot{V}O_2$ (Nolte et al., 2023). The following parameters were assessed to check physical exhaustion and thus $\dot{V}O_2max$. The highest value of the respiratory exchange ratio (quotient of $\dot{V}CO_2$/ $\dot{V}O_2$) at the end of the exercise was identified as RER_{end}. The maximal heart rate (HRmax) was assessed using a chest strap (H7 or H10; Polar Electro; Kempele; Finland). In addition, the session rate of perception of exertion (sRPE) was queried after test termination. Immediately after the test, 20 µL of capillary blood was collected from the right earlobe to assess the maximal lactate concentration reached during the treadmill test (La_{end}). At least two of the following exercise criteria had to be fulfilled (Billat & Koralsztein, 1996). $RER_{end} \geq 1.0$; sRPE ≥ 17; HRmax ≥ 210-age, $La_{end} \geq 8$ mmol/L, and reaching a $\dot{V}O_2$ plateau. The MAS represents the first (interpolated) velocity when reaching this plateau (Billat & Koralsztein, 1996; Thron, Woll, et al., 2022). ASR was determined as the speed difference between MSS and MAS. Furthermore, the SRR was quantified as the quotient of MSS and MAS.

4.3.4 Statistical analysis

Statistical analysis was carried out with RStudio (Team, 2022). Normality and homogeneity of variance were checked and confirmed by the Kolmogorov-Smirnov and Levene tests, respectively. To detect possible differences between the subgroups regarding the physiological and locomotor parameters, a two-way analysis of variance (ANOVA, discipline (sprint, 400m, middle-distance)*sex (female, male)) was conducted. Posthoc comparisons was based on Bonferroni's correction. The effect sizes of the ANOVA results were estimated by partial eta^2: $0.01 \leq \eta_p^2 < 0.06$ is considered a small, $0.06 \leq \eta_p^2 < 0.14$ a medium, and $0.14 \geq \eta_p^2$ a large effect (Cohen, 1988). The effect sizes (d) of the posthoc tests were calculated using Cohen's d: $0.2 \leq d < 0.5$ represent small, $0.5 \leq d < 0.8$ medium, and $d \geq 0.8$ represent large effects (Cohen, 1988). In addition, equivalence testing based on the two one-sided tests (TOST) was used to assess if an observed effect is as extreme as the smallest effect size of interest (SESOI) (Lakens et al., 2018). As previously suggested, the SESOI was calculated with a power analysis at 33% power and the respective sample sizes of the subgroups (sprint and 100-m: SESOI=0.65; sprint and middle-distance: SESOI=0.63; 400-m and middle-distance: SESOI=0.63) (Simonsohn, 2015). The Pearson's correlation coefficient was calculated to detect relationships between physiological and locomotor parameters. According to Hopkins (2004), the magnitude of the correlation was considered to be small ($0.1 \leq r < 0.3$), medium ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), and almost perfect ($r \geq 0.9$) classifications. The significance level for all calculations was set at $\alpha = 0.05$.

4.4 Results

The criteria for achieving physical exhaustion and thus $\dot{V}O_2max$ were met by the N=34 participants included in the further analysis. The mean age, the average expertise, and the average WA scores were similar between the subgroups (p>0.05). The descriptive results for each parameter by discipline and sex are illustrated in Figure 4.1. Scatterplots including the median for the respective parameter and information about the individual WA scores are shown in Figure 4.2 for males and in Figure 4.3 for females. The main effect for the sex comparison showed significant differences ($p \leq 0.01$; see Table 4.2) between male and female with medium to large effect sizes ($0.27 \leq \eta_p^2 \leq 0.77$; $0.71 \leq d \leq 2.53$) and non-significant results for the equivalence testing ($0.71 \leq p \leq 1.00$; see Table 4.2) for MSS, ASR, $\dot{V}O_2max$, and ċLamax. For MAS, no significant difference between male and female but medium to large effects ($p=0.07$; $\eta_p^2=0.37$; $d=1.11$; TOST: $p=0.95$) were found. The main effect for discipline revealed significant and large effects ($p<0.01$; $0.30 \leq \eta_p^2 \leq 0.67$) for all of the investigated parameters; except for $\dot{V}O_2max$ showing a non-significant but large effect ($p=0.11$; $\eta_p^2=0.37$). Additionally, the Bonferroni posthoc tests indicated a significantly lower MAS and $\dot{V}O_2max$ for sprinters than for 400-m runners and compared to middle-distance runners ($p \leq 0.02$; $-2.24 \leq d \leq -1.29$; TOST: $0.93 \leq p \leq 1.00$). The differences between 400-m and middle-distance runners were non-significant with small to very large effect sizes and non-significant results for the equivalence testing ($0.28 \leq p \leq 1.00$; $-0.33 \leq d \leq -0.74$; TOST: $0.24 \leq p \leq 0.59$). For MSS and ċLamax, the comparison of sprinters and 400-m runners did not show a significant difference ($0.83 \leq p \leq 1.00$; $.0.02 \leq d \leq 0.480$; TOST: $0.08 \leq p \leq 0.35$), whereby the comparisons of the sprinters and middle-distance runners as well as 400-m and middle-distance runners showed medium to large effect sizes ($0.03 \leq p \leq 0.28$; $0.73 \leq d \leq 1.23$; TOST: $0.59 \leq p \leq 0.91$). ASR and SRR were significantly higher for sprinters than for 400-m runners and compared to middle-distance runners, and also higher for 400-m than for middle-distance runners ($p \leq 0.03$; $1.24 \leq d \leq 3.15$; TOST: $0.91 \leq p \leq 1.00$). In addition, the interaction between sex and discipline was not significant for any parameter with trivial to small effect sizes ($0.12 \leq p \leq 0.84$; $0.00 \leq \eta_p^2 \leq 0.08$).

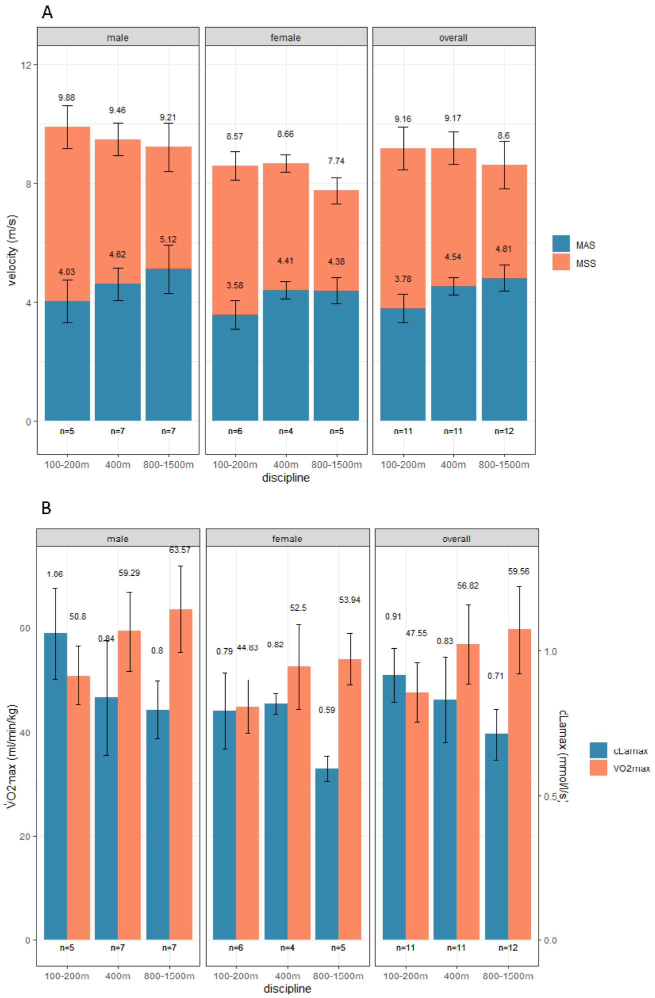

Figure 4.1: Overview of descriptive results. A: Mean values and standard deviations of maximal aerobic speed (MAS) and maximal sprinting speed (MSS) for 100–200m (sprinters), 400-m, and 800–1500m-runners (middle-distance runners) for males, females, and overall. B: Mean values and standard deviations of maximal rate of lactate accumulation (ċLamax) and maximal oxygen consumption ($\dot{V}O_2max$) for 100–200m (sprinters), 400-m, and 800–1500m-runners (middle-distance runners) for males, females, and overall.

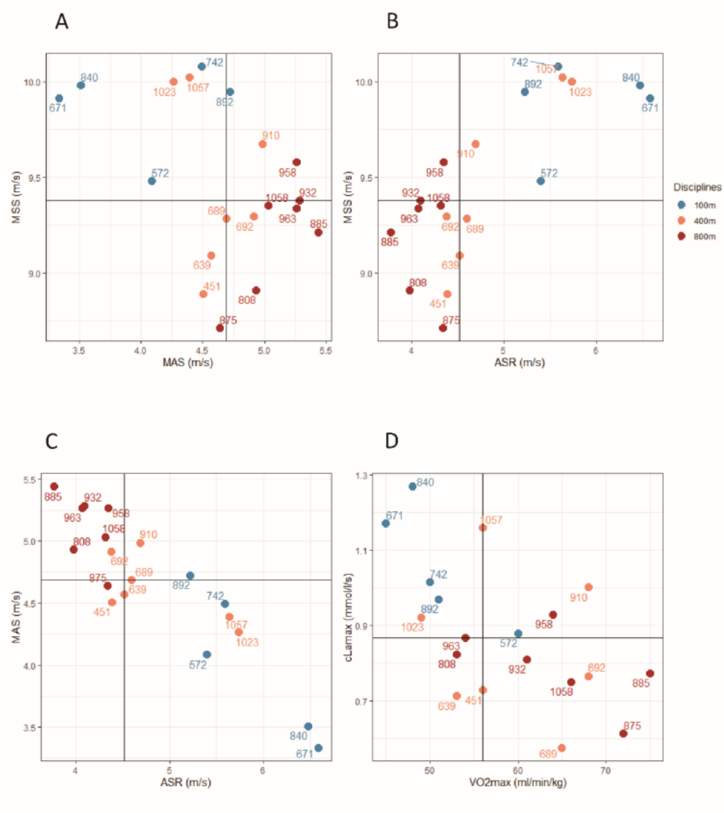

Figure 4.2: Scatterplots for male participants with blue dots for 100–200-m sprinters, orange dots for 400-m runners, and red dots for 800–1500m-runners (middle-distance runners). The vertical and horizontal lines represent the median of the respective parameter and the numbers represent the individual World Athletics scores (Spiriev, 2022). A: Maximal aerobic speed (MAS) and maximal sprinting speed (MSS). B: Anaerobic speed reserve (ASR) and maximal sprinting speed (MSS). C: Anerobic speed reserve (ASR) and maximal aerobic speed (MAS). D: Maximal rate of lactate accumulation (ċLamax) and maximal oxygen uptake ($\dot{V}O_2$max).

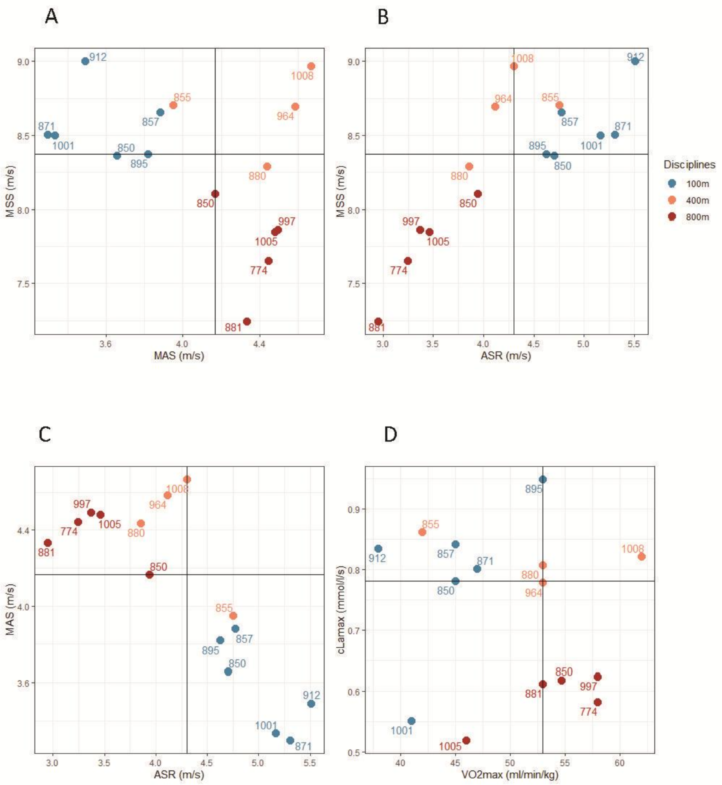

Figure 4.3: Scatterplots for female participants with blue dots for 100–200-m sprinters, orange dots for 400-m runners, and red dots for 800–1500m-runners (middle-distance runners). The vertical and horizontal lines represent the median of the respective parameter and the numbers represent the individual World Athletics scores (Spiriev, 2022). A: Maximal aerobic speed (MAS) and maximal sprinting speed (MSS). B: Anaerobic speed reserve (ASR) and maximal sprinting speed (MSS). C: Anerobic speed reserve (ASR) and maximal aerobic speed (MAS). D: Maximal rate of lactate accumulation (ċLamax) and maximal oxygen uptake ($\dot{V}O_2max$).

Table 4.2: Results of ANOVA (interaction, sex, discipline) with Bonferroni post-hoc tests (100-200m vs. 400, 100-200m vs. 800-1500m, 400m vs. 800-1500m) and equivalence testing for locomotor (MAS, MSS, ASR, SRR) and physiological ($\dot{c}$Lamax, $\dot{V}O_2$max) performance.

		Mean ± SD	MD (95% CI)	p	ηp2 (95% CI)	d (95% CI)	TOST (p)
MAS [m/s]	**Interaction**	-	-	0.37	0.03 (0.00–0.21)	-	-
	Sex	**Male**: 4.65 ± 0.57 **Female**: 4.07 ± 0.47	0.58 (0.22–0.94)	0.07	0.37 (0.11–0.57)	1.11 (0.45–2.13)	0.95
	Discipline	100m: 3.78 ± 0.48 400m: 4.53 ± 0.29 800m: 4.81 ± 0.44	-	<0.01**	0.63 (0.40–0.76)	-	-
	100-200m vs. 400m	-	-0.76 (-1.12–-0.40)	<0.01**	-	-1.91 (-4.33–-0.96)	0.99
	100-200m vs. 800-1500m	-	-1.03 (-1.43–-0.63)	<0.01**	-	-2.24 (-4.13–-1.4)	1.00
	400m vs. 800-1500m	-	-0.27 (-0.59–0.05)	0.28	-	-0.74 (-1.72–0.05)	0.59
MSS [m/s]	**Interaction**	-	-	0.63	0.01 (0.00–0.16)	-	-
	Sex	Male: 9.48 ± 0.42 Female: 8.32 ± 0.50	1.16 (0.83–1.49)	<0.01**	0.77 0.61–0.86)	2.53 (2.00–3.52)	1.00
	Discipline	100m: 9.16 ± 0.72 400m: 9.17 ± 0.55 800m: 8.60 ± 0.81	-	<0.01**	0.34 (0.09–0.55)	-	-
	100-200m vs. 400m	-	-0.01 (-0.58–0.56)	1.00	-	-0.02 (-0.95–0.88)	0.08
	100-200m vs. 800-1500m	-	0.56 (-0.10–1.23)	0.28	-	0.73 (-0-05–1.68)	0.59
	400m vs. 800-1500m	-	0.57 (-0-06–1.17)	0.18	-	0.83 (0.10–1.67)	0.67
ASR [m/s]	**Interaction**	-	-	0.82	0.00 (0.00–0.11)	-	-
	Sex	Male: 4.85 ± 0.83 Female: 4.27 ± 0.79	0.58 (0.01–1.15)	<0.01**	0.72 (0.52–0.82)	0.71 (0.08–1.41)	0.71
	Discipline	100m: 5.39 ± 0.65 400m: 4.63 ± 0.58 800m: 3.82 ± 0.47	-	<0.01**	0.43 (0.17–0.63)	-	-
	100-200m vs. 400m	-	0.76 (0.22–1.31)	0.03*	-	1.24 (0.36–2.51)	0.91
	100-200m vs. 800-1500m	-	1.57 (1.07–2.07)	<0.01**	-	2.79 (2.24–4.04)	1.00
	400m vs. 800-1500m	-	0.81 (0.35–1.27)	<0.01**	-	1.53 (0.95–2.39)	0.98

SRR	**Interaction**	-	-	0.84	0.00 (0.00–0.11)	-	-
	Sex	Male: 2.08 ± 0.35 Female: 2.08 ± 0.32	0.00 (-0.24–0.24)	0.99	0.02 (0.00–0.20)	0.00 (-0.78–0.70)	0.07
	Discipline	100m: 2.45 ± 0.28 400m: 2.03 ± 0.17 800m: 1.80 ± 0.08	-	<0.01**	0.67 (0.46–0.79)	-	-
	100-200m vs. 400m	-	0.42 (0.21–0.63)	<0.01**	-	1.83 (1.22–3.16)	0.99
	100-200m vs. 800-1500m	-	0.65 (0.46–0.85)	<0.01**	-	3.15 (2.56–4.81)	1.00
	400m vs. 800-1500m	-	0.23 (0.11–0.35)	<0.01**	-	1.73 (1.27–2.84)	0.99
V̇O₂max [mL/min/kg]	**Interaction**	-	-	0.57	0.01 (0.00–0.17)	-	-
	Sex	Male: 58.60 ± 8.74 Female: 49.90 ± 7.04	8.72 (3.20–14.20)	<0.01**	0.27 (0.04–0.49)	1.10 (0.5–1.9)	0.95
	Discipline	100m: 47.50 ± 5.97 400m: 56.80 ± 8.18 800m: 59.60 ± 8.45	-	0.11	0.37 (0.11–0.58)	-	-
	100-200m vs. 400m	-	-9.27 (-15.70–-2.86)	0.02*	-	-1.29 (-2.54–-0.44)	0.93
	100-200m vs. 800-1500m	-	-12.0 (-18.3–-5.68)	<0.01**	-	-1.64 (-2.83–-0.92)	0.99
	400m vs. 800-1500m	-	-2.74 (-9.96–4.48)	1.00	-	-0.33 (-1.32–0.55)	0.24
ċLamax [mmol/L/s]	**Interaction**		-	0.62	0.01 (0.00–0.17)	-	-
	Sex	Male: 0.88 ± 0.19 Female: 0.73 ± 0.13	0.15 (0.04–0.26)	0.01*	0.29 (0.06 – 0.1)	0.92 (0.30–1.66)	0.88
	Discipline	100m: 0.92 ± 0.20 400m: 0.83 ± 0.16 800m: 0.71 ± 0.13	-	<0.01**	0.30 (0.06–0.52)	-	-
	100-200m vs. 400m		0.08 (-0.73–0.24)	0.83	-	0.48 (-0.36–1.5)	0.35
	100-200m vs. 800-1500m		0.20 (0.06–0.35)	0.03*	-	1.23 (0.46–2.41)	0.91
	400m vs. 800-1500m		0.12 (-0.01–0.25)	0.18	-	0.83 (0.03–1.86)	0.61

MAS – maximal aerobic speed; MSS – maximal sprinting speed; ASR – anaerobic speed reserve; SRR – speed reserve ratio; ċLamax – maximal rate of lactate accumulation; V̇O₂max – relative maximal oxygen update; 100-200m – sprinters; 400m – 400-m runners; 800-1500m – middle-distance runners; SD – standard deviation; MD – mean difference; 95 % CI – 95 % confidence interval; p – significance value; η_p^2 – effect size, i.e., partial squared eta; d – effect size, i.e., Cohen's d; TOST – results for equivalence testing, i.e., two one-sided tests; * indicates p<0.05; ** indicates p<0.01.

ASR showed very large to almost perfect positive correlations with MSS, SRR, and $\dot{c}La_{max}$ ($p<0.01$; $0.73 \leq r \leq 0.91$, see Table 4.3) and medium to large negative correlations with MAS and $\dot{V}O_2max$ ($p<0.05$; $-0.55 \leq r \leq -0.39$). SRR showed medium to large positive correlations with MSS and $\dot{c}La_{max}$ ($p<0.05$; $0.39 \leq r \leq 0.56$) and large to very large negative correlations with MAS and $\dot{V}O_2max$ ($p<0.01$; $-0.83 \leq r \leq -0.60$). In addition, very large relationships were found between MAS and $\dot{V}O_2max$ ($p<0.01$; $r=0.75$) and between MSS and $\dot{c}La_{max}$ ($p<0.01$; $r=0.74$). Additional correlation analysis showed a large negative relationship between WA scores and $\dot{V}O_2max$ for the sprinters ($p<0.05$; $r=-0.62$) and a large positive relationship between WA scores and $\dot{c}La_{max}$ for 400-m runners ($p<0.05$; $r=0.68$).

Table 4.3: Correlation matrix showing Pearson's r (95% confidence intervals).

	MAS	**MSS**	**ASR**	**SRR**	**ċLamax**
MSS	0.17 (-0.17–0.48)	-	-	-	-
ASR	-0.55** (-0.75–-0.26)	0.73** (0.51–0.85)	-	-	-
SRR	-0.83** (-0.91–-0.68)	0.39* (0.06–0.64)	0.91** (0.83–0.95)	-	-
ċLamax	-0.16 (-0.47–0.19)	0.74** (0.54–0.86)	0.74** (0.53–0.86)	0.56** (0.28–0.76)	-
$\dot{V}O_2max$	0.75** (0.56–0.87)	0.15 (-0.20–0.46)	-0.39* (-0.64–-0.06)	-0.60** (-0.78–-0.33)	-0.15 (-0.47–0.19)

MAS – maximal aerobic speed; MSS – maximal sprinting speed; ASR – anaerobic speed reserve; SRR – speed reserve ratio; ċLamax – maximal rate of lactate accumulation; $\dot{V}O_2max$ – relative maximal oxygen update; * indicates $p<0.05$; ** indicates $p<0.01$.

4.5 Discussion

Physiological (i.e., based on $\dot{c}La_{max}$ and $\dot{V}O_2max$) and locomotor profiling (i.e., based on MAS, MSS, and ASR) seem to be promising approaches to evaluate performance outcomes in running (Hallam et al., 2022; Lundby et al., 2017; Sandford et al., 2021). Therefore, our study aimed to compare physiological and locomotor profiles of adolescent and young adult male and female sprinters, 400-m runners, and middle-distance runners and examine relationships between the respective approaches. MAS, MSS, ASR, $\dot{V}O_2max$, and $\dot{c}La_{max}$ showed higher absolute values in males than in females, whereas no significant sex difference can be found for SRR. Moreover, the results of our study demonstrated that the profiles differ depending on the discipline. The comparison of the disciplines revealed significantly higher values in MAS and $\dot{V}O_2max$ for 400-m and middle-distance runners compared to sprinters. In contrast, the sprinters and 400-m runners showed higher results in MSS and $\dot{c}$Lamax than the middle-distance group. ASR and SRR were significantly higher for sprinters than for 400-m runners and middle-distance runners, and also higher for 400-m compared to middle-distance runners. ASR and SRR are highly correlated with all of the investigated parameters, i.e., MSS, MAS, $\dot{c}$Lamax, and $\dot{V}O_2max$. Additionally, MAS shows a strong relationship with $\dot{V}O_2max$, whereby MSS is correlated to $\dot{c}$Lamax.

Our results indicate that the physiological profiles, i.e., the characteristics of $\dot{c}$Lamax and $\dot{V}O_2max$, differ between the subgroups and that the 400-m runners show a similar anaerobic power (i.e., $\dot{c}$Lamax) to the sprinters but also a similar aerobic capacity (i.e., $\dot{V}O_2max$) to the middle-distance runners. This might be explained by previous findings reporting that 400-m performance is equally explained by aerobic and anaerobic energy supply (i.e., $\dot{V}O_2max$ and accumulated oxygen deficit, respectively) whereas the 100-m performance is mostly explained by anaerobic and the 800-m performance by aerobic energy supply (Nevill et al., 2008; Quittmann et al., 2020). Within the 400-m group, the athletes with the highest WA scores also show higher $\dot{c}$Lamax than the athletes with lower WA scores (see Fig. 4.2D). However, this is not evident for $\dot{V}O_2max$. These results might indicate that a high anaerobic power is more important for a high 400-m performance than a high aerobic capacity. The higher results of $\dot{V}O_2max$ and $\dot{c}$Lamax for the males compared to the females are in line with previous research and might be due to differences in muscle mass and muscle fibre distributions (Quittmann et al., 2023). Additionally, because of the mathematical dependency (see Eq. (1)), the $\dot{c}$Lamax is affected by t_{100} which was higher for the females compared to the males (13.43 ± 0.81 s and 11.86 ± 0.46 s, respectively) resulting in lower $\dot{c}$Lamax for the females compared to the males.

Similar to the physiological profile, the results regarding the locomotor profile, i.e., MAS, MSS, and ASR, differ between the subgroups. The MAS of female 400-m runners was descriptively comparable to the MAS of female middle-distance runners, but the MAS of male 400-m runners was lower than for middle-distance runners (see Fig. 4.1A, Fig. 4.2A, and Fig. 4.3A). These results are in line with Sandford, Allen, et al. (2019) and Hallam et al. (2022) showing a higher MAS for middle-distance runners compared to 400-m runners in men and similar results in MAS for 400-m and middle-distance runners in women. Because of the MAS being based on $\dot{V}O_2$-kinetics these results can be explained by differences in muscle mass and fibre distributions between men and women (Quittmann et al., 2023). Although our results regarding MSS did not reveal any significant differences between the disciplines, the descriptive results show a trend towards higher MSS for sprinters and 400-m runners compared to middle-distance runners. These results are also evident in the participants' WA scores (see Fig 4.2A and B, and Fig. 4.3A and B). The 400-m runners with the highest WA scores partly show the highest values for ASR, MSS (males and females), and MAS (only females). Previous studies have already found a significantly higher MSS for 400-m compared to 800-m or 1500-m runners (Hallam et al., 2022; Sandford, Allen, et al., 2019). These results could be explained by mechanical and neuromuscular variations affecting MSS between the athletes and subgroups (Cunningham et al., 2013). In addition, differences in kinematic variables such as shorter ground contact time, higher knee range of motion and stride length of sprinters compared to middle-distance runners can affect MSS (Cunningham et al., 2013). Moreover, our findings that ASR and SRR are highest in sprinters and the lowest in middle-distance runners is also in line with previous research (Hallam et al., 2022; Sandford, Allen, et al., 2019). Especially for 400-m running performance, a high ASR seems to be beneficial (see Fig. 4.2B). The sex differences of ASR, i.e., higher ASR for males than for females, could mainly result from the higher MSS in men compared to women while MAS on average did not differ between sexes. These results may indicate that women show a lower tolerance to high-intensity exercise than men resulting in the need of different training stimuli such as differences in intensity, volume, or density to avoid overload or overtraining (Sandford et al., 2021). However, SRR does not show differences between males and females, indicating that although MSS differs between sexes, the proportions of MAS and MSS are similar. Therefore, SRR might reflect a way to normalize the ASR based on a ratio and makes it possible to compare different characterized groups like males and females. However, for (longitudinal) performance evaluation, the absolute values of MAS and MSS should always be taken into consideration.

In sum, our results regarding the locomotor profile, i.e., MAS, MSS, and ASR, and the physiological profile, i.e., $\dot{c}$Lamax and $\dot{V}O_2max$, indicate that 400-m runners show MSS and $\dot{c}$Lamax comparable to sprinters and a MAS and $\dot{V}O_2max$ comparable to middle-distance runners. These results are even more explicit for the 400-m runners with the highest WA scores which might help to detect strengths and weaknesses of athletes, e.g. for talent identification (Hallam et al., 2022). Nonetheless, the locomotor profile based on the ASR holds the advantage of distinguishing between the three subgroups and selecting training priorities for each profile. Sandford et al. (2021) suggest to categorize athletes based on their locomotor variables to define the best possible stimuli for endurance training based on the profiles, namely speed (high ASR; high MSS), hybrid (moderate ASR, moderate MSS), and endurance types (low ASR, high MAS). However, because no valid normative values for these profiles exist in the literature, the participants in our study can only be categorized based on group comparisons of the underlying sample. The sprinters in this study can be assigned to the speed profile indicating optimal adaptations when repeated sprints and short intervals are conducted. The middle-distance runners can be assigned to the endurance profile and may therefore be best suited to higher volumes and slow continuous efforts. Because 400-m runners show high characteristics in both MAS and MSS, they can be assigned to both types. Therefore, 400-m runners might tolerate higher volumes but also higher intensities (Sandford et al., 2021). However, the optimal prescription of training for different types of profiles needs to be investigated in the future.

Regarding the relationships among the various markers, our findings indicate that the aerobic parameters MAS and $\dot{V}O_2max$ are positively correlated with each other. Similarly, the more anaerobically or mechanically connotated parameters MSS and $\dot{c}Lamax$ are also positively correlated. However, no relations were identified between aerobic and anaerobic-mechanical markers. These results point towards an independency of oxidative and glycolytic parameters. Due to ASR and SRR being based on both MAS and MSS, they negatively correlate with aerobic (i.e., $\dot{V}O_2max$, MAS) but positively with anaerobic-mechanical parameters (i.e., $\dot{c}Lamax$, MSS). Athletes with a high ASR and SRR also show a high MSS and $\dot{c}Lamax$ but a low MAS and $\dot{V}O_2max$ (see Fig. 4.2B and C, and Fig. 4.3B and C). Alongside with the results for the differences in these parameters between the disciplines, these results indicate that physiological and locomotor profiles are related to each other and that both can differentiate the different subgroups.

Limitations

The results of this study have to be interpreted with respect to its limitations. A major limitation of this study is the fairly small sample size with subgroups regarding disciplines of n=11 – 12 participants, due to the difficulty in recruiting high-level athletes. Additionally, the age of the participants ranged from 15 to 23 years. Although all of the athletes already competed in national and international competitions, performance differences due to the experience in training or maturation cannot be precluded (Mota et al., 2002). However, the age range, the average expertise, and the average WA scores were similar between the subgroups ($p>0.05$), thereby enhancing their comparability. In addition, the 100-m sprints had to be conducted with different environmental conditions, i.e., some participants sprinted on an indoor track and some on an outdoor track dependent on the facilities which were available close to the athletes' training facilities. Although, the flooring consisted of Tartan™ on both tracks which is an important influencing factor in sprinting, conditions like higher temperature or wind could have influenced the sprinting performance (Haugen & Buchheit, 2016). The mean temperature and wind speed during the indoor sprints were 19.3°C (18.6–19.9°C) with 0 m/s wind and during the outdoor sprints 17.9°C (17.0–18.5°C) and 1.3 (0.6–1.9 m/s). However, the number of athletes that were tested outdoors and indoors were balanced between the groups. There is still a research gap regarding the application of profiling, for example in training prescription or load monitoring, which should be addressed in the future (Sandford et al., 2021).

Practical applications

Practitioners should be aware that adolescent and young adult sprinters show higher characteristics in anaerobic or neuromuscular-mechanical markers, whereas middle-distance runners exhibit higher aerobic markers. 400-m runners, especially those with high personal best times and WA scores, combine both high anaerobic and neuromuscular-mechanical as well as high aerobic characteristics. Our results indicate that physiological and locomotor profiling can be used to distinguish between different sprinting and running disciplines in adolescents and young adults which might be helpful for assessing strengths and weaknesses, e.g. for talent identification, or to assess adaptations over time. Additionally, the knowledge about the respective profile (Sandford et al., 2021) can help choosing the optimal training stimuli for either adapting some characteristics of the profile or to support the current characteristics, e.g., higher volumes and lower intensities for endurance profiles or lower volumes and higher intensities for speed profiles. Moreover, physiological and locomotor approaches provide a similar description of athletes' aerobic and anaerobic-mechanical capabilities. However, locomotor profiling adds the advantage that training, e.g. high-intensity interval training, can be individually prescribed based on ASR (Buchheit & Laursen, 2013b).

4.6 Conclusion

To conclude, our results indicate that athletes of different running disciplines show differing physiological and locomotor profiles. Sprinters show higher anaerobic-mechanical but lower aerobic characteristics than middle-distance runners. The 400-m runners have high anaerobic-mechanical as well as aerobic markers which is even more explicit for the athletes with the highest WA scores. Hence, the ASR can be used to categorize the sprinters into speed and the middle-distance runners into endurance profiles, while the 400-m runners fit in both profiles. In addition, high correlations between the markers for physiological and locomotor profiling indicate that these approaches are related to each other and that both can differentiate the different subgroups.

5 Methods to Assess the Locomotor Profile (Anaerobic Speed Reserve) (Papers II – IV)

5.1 Validity of Field Tests to Assess Maximal Aerobic Speed (Paper II)

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5.1.1 Abstract

Introduction. Maximal aerobic speed (MAS), usually measured by cardiopulmonary exercise testing (CPET) on a treadmill, is gaining popularity in soccer to determine aerobic performance. Several field tests are used to estimate MAS, although, gold standard methods are still not clarified. Therefore, this work aims i) to compare two different CPET based methods to assess MAS and ii) to investigate the convergent validity of two common field tests to estimate MAS in soccer. **Methods.** Thirteen trained male soccer players completed an CPET on a treadmill to determine two VO_2-kinetic based definitions of MAS ($MAS_{Plateau}$=speed at onset of VO_2-plateau=gold standard; MAS_{30s}=first speed of 30-s-interval of $\dot{V}O_2max$), the Université de Montreal Track Test (UMTT; V_{UMTT}=speed of the last stage), and a 1500-m-time trial (1500-m-TT; V_{1500m}=average speed). $MAS_{Plateau}$, MAS_{30s}, V_{UMTT}, and V_{1500m} were compared using ANOVA. Additionally, limits of agreement analysis (LoA), Pearson's r, and ICC were calculated between tests. **Results.** MAS_{30s}, $V_{UMTT,}$ and V_{1500m} significantly overestimated $MAS_{Plateau}$ by 0.99 km/h (ES=1.61; p<0.01), 1.61 km/h (ES=2.03; p<0.01) and 1.68 km/h (ES=1.77; p<0.01), respectively, with large LoA (-0.21≤LoA≤3.55), however with large-to-very large correlations (0.65≤r≤0.87; p≤0.02; 0.51≤ICC≤ 0.85; p≤0.03). **Discussion.** The overestimation and large LoA of $MAS_{Plateau}$ by all estimates indicate that i) a uniform definition of MAS is needed and ii) the UMTT and a 1500-m-TT seem questionable for estimating MAS for trained soccer players on an individual basis, while regression equations might be suitable on a team level. The results of the present work contribute to the clarification of acquisition of MAS in soccer.

5.1.2 Introduction

Given the high cardiorespiratory demands during a soccer match, in which professional players cover a distance up to 13 km, assessment of endurance performance with subsequent individual training prescription seems indispensable (Altmann et al., 2020; Tanner & Gore, 2012). Aerobic performance is often assessed by measuring the maximum oxygen uptake ($\dot{V}O_2max$). In soccer, $\dot{V}O_2max$ is significantly related to the distance covered during a match and reflects aerobic capacity (Aquino et al., 2020; Bangsbo et al., 1991). The $\dot{V}O_2max$ is commonly assessed by cardiopulmonary exercise testing (CPET) on a treadmill with incremental protocols (Kuipers et al., 2003; Riboli et al., 2022). A criterion for obtaining the true $\dot{V}O_2max$ in such tests is the occurrence of a VO_2-plateau which is defined by a lower increase in VO_2 than 150 ml/min in at least the last minute of an incremental exercise (Meyer & Kindermann, 1999). Then, $\dot{V}O_2max$ is defined as the maximal 30-s-interval of VO_2 during an incremental CPET usually occurring at the termination of the test due to exhaustion. However, while being mainly an aerobic marker, $\dot{V}O_2max$ is reached with efforts above the onset of the plateau associated with a higher input of anaerobic resources (Billat & Koralsztein, 1996). Therefore, the way $\dot{V}O_2max$ is commonly measured, it incorporates not only aerobic but to some extent also anaerobic resources. Importantly, the anaerobic contribution can largely differ between athletes. This leads to different lengths of the VO_2-plateau until exhaustion is reached, thereby distinguishing between athletes depending on their utilization of anaerobic resources. More specifically, athletes mainly relying on aerobic resources show a short VO_2-plateau, whereby athletes using a greater amount of anaerobic resources display a longer plateau (Petot et al., 2012). As the velocity associated with the 30-s-interval of $\dot{V}O_2max$ is commonly used for prescribing training intensities, it might trigger the aerobic and anaerobic energy pathways to different extents depending on the physiological profile of the respective athlete possibly leading to a non-optimal training adaptation. A parameter that addresses the mentioned shortcomings of $\dot{V}O_2max$ is the maximal aerobic speed (MAS) which has recently gained popularity in scientific literature and practice. The MAS was firstly described by Di Prampero et al. (1986) as the minimum speed at which VO_2-consumption stops increasing despite a further increase in load, i.e., the onset of the VO_2-plateau, in the current study referred to as $MAS_{Plateau}$. Based on $MAS_{Plateau}$, training intensities aiming to address mainly aerobic resources to the same extent for different athletes can be set. CPET on a treadmill is used as a gold standard method to assess MAS. Nevertheless, different treadmill protocols and definitions of MAS exist, which also provide different results (Berthoin et al., 1996; Billat et al., 1996; Riboli et al., 2022). Besides $MAS_{Plateau}$, the velocity of the 30-s-interval of $\dot{V}O_2max$ (MAS_{30s}) is often applied as an alternative method to assess MAS (Buchheit, 2008; Sandford, Rogers, et al., 2019). However, to date, no studies compared the currently most common definitions based on examination of VO_2-kinetics, i.e., first velocity at onset of VO_2-plateau ($MAS_{Plateau}$) and the first velocity of 30-s-interval of $\dot{V}O_2max$ (MAS_{30s}).

Despite ambiguities in the gold standard method, simplified methods in the field are used to estimate MAS, such as incremental continuous field tests like Université de Montréal Track Test (UMTT) or different set time and distance trials (TT) (Bangsbo et al., 2008; Clarke et al., 2016; Léger & Boucher, 1980; Léger et al., 1988; Sandford, Rogers, et al., 2019). In terms of the validity of the UMTT, Berthoin et al. (1996) and Souza et al. (2014) could not find any significant differences between MAS and V_{UMTT}, whereas Lacour et al. (1991) revealed an overestimation of MAS by V_{UMTT}. Regarding set distance time trials to assess MAS, the current literature also reveals conflicting results. Set distance TT yielded similar results (Bellenger et al., 2015; Lundquist et al., 2021; Souza et al., 2014) or over-estimated MAS and V_{UMTT} (Darendeli et al., 2021; Sandford, Rogers, et al., 2019). Due to contrary results in the current literature on field tests to estimate MAS, Buchheit (2010) proposed to distinguish the results obtained from CPET, from those obtained from field tests by designating the values obtained from CPET as MAS and the estimates from a field test as V_{Test}. This reinforces the importance of reporting exact definitions and methods. Furthermore, most of the above-mentioned studies were conducted with runners and sports students, which does not allow for a clear conclusion about soccer.

To address these shortcomings, the aims of this study were 1) to compare two different VO_2-kinetic based methods, i.e., first velocity at onset of VO_2-plateau ($MAS_{Plateau}$) and first velocity of 30-s-interval of $\dot{V}O_2max$ (MAS_{30s}), using CPET on a treadmill, and 2) to investigate convergent validity of both the UMTT and a 1500-m-TT in relation to a VO_2-kinetic based MAS, i.e. $MAS_{Plateau}$, in soccer. Thus, this work contributes to clarify the implementation of the gold standard method for assessing MAS in soccer and whether the assessment can be simplified by the UMTT or a 1500-m-TT.

5.1.3 Methods

Study Design

Thirteen trained male soccer players performed three tests at three different occasions, with a minimum of 7 and a maximum of 21 days between the tests and a training rest of at least 24 hours before each test. Tests were conducted in the same order for all participants: 1) UMTT on a 400-m-running track, 2) CPET on a treadmill, and 3) a 1500-m-TT on a 400-m-running track. During the incremental treadmill test, $MAS_{Plateau}$ [km/h] and MAS_{30s} [km/h] were determined by examining the VO_2-kinetics. Moreover, the main parameters measured during field testing were: V_{UMTT} [km/h], V_{1500m} [km/h], and V_{calc} [km/h]. MAS_{30s}, V_{UMTT}, V_{1500m}, and V_{calc} were compared to $MAS_{Plateau}$ which is considered as the gold standard method in the current study.

Sample

The sample consisted of n=13 trained male soccer players classified as tier 2 athletes (McKay et al., 2022) (mean±SD: age: 25.38±2.75 years; height: 178.51±7.82 cm; weight: 78.60±8.85 kg; fat mass proportion: 16.86±4.78 %; $\dot{V}O_2max$: 49.92±3.15 ml/kg/min; exercise frequency: 4.50±0.50 times/week; soccer experience: 21.67±3.40 years). Players' health was checked and confirmed by the Physical Activity Readiness-Questionnaire (Tremblay et al., 2012). Each subject was informed about the study procedure and possible risks and agreed to participate by signing a consent form. As per the local legislation, this study was exempt from full ethics review by the institutional review board, due to this being an anonymous study containing anonymous data. To avoid bias, goal keepers were excluded from this study (Altmann et al., 2020).

Université de Montréal Track Test (UMTT)

The UMTT was conducted on a 400-m-tartan track. Large cones were placed at 50-m-intervals, small cones after the first 33.33 m and at 100-m-intervals. The speed was controlled by an acoustic signal at which the cones had to be reached. The initial speed was set at 10 km/h and every 2 min the speed was increased by 1 km/h (Bellenger et al., 2015; Berthoin et al., 1996; Billat & Koralsztein, 1996; Darendeli et al., 2021). Each subject was equipped with a previously validated chest strap (H7 or H10, Polar Electro, Kempele, Finland) for monitoring HR (Hernández-Vicente et al., 2021; Speer et al., 2020). The test was completed as soon as the subject was no longer able to reach the specified cone at the acoustic signal. V_{UMTT} was determined as the speed of the last stage. If the last stage had not been finished, V_{UMTT} was calculated using the following formula: V_{UMTT}=speed of the last completed stage [km/h]+time in last stage [s]/120 s (Berthoin et al., 1996). In addition, the $HRmax_{UMTT}$ and RPE_{UMTT} were recorded after the end of the test to assess physical exhaustion.

Cardiopulmonary exercise testing (CPET)

To assess $MAS_{Plateau}$ and MAS_{30s}, CPET on a treadmill with ±0.1 km/h speed accuracy was performed (Woodway PPSmed 55 and PPSmed L70; WOODWAY GmbH; Weil am Rhein; Germany). The test protocol started at 6 km/h and increased every 3 min by 2 km/h with a treadmill incline of 1% to reflect the energy expenditure of outdoor running (Jones & Doust, 1996). Between each stage, the subject rested for 0.5 min and the test got terminated by the subject due to voluntary exhaustion (Dickhuth & Badtke, 2007). Breath-by-breath ventilatory data were obtained using the Metalyzer 3B spirometer and the appropriate MetaSoft 3 software (Cortex Biophysik GmbH; Leipzig; Germany) with which the data was prepared as 15-second moving average values for further analysis. This technology enables accurate and precise determination of the individual VO_2-kinetics (Vogler et al., 2010). Gas sensors were calibrated using gases of known concentrations

(15% O_2, 5% CO_2), and the turbine volume transducer was calibrated using a 3-l syringe (Cortex Biophysik GmbH; Leipzig; Germany).

The VO_2-data were first examined for a plateau which is defined as a lower increase in VO_2 than 150 ml/min in at least the last minute of exercise (Meyer & Kindermann, 1999). The $MAS_{Plateau}$ represents the first velocity when reaching this plateau (Billat & Koralsztein, 1996). Additionally, the velocity at the onset of the 30-s-interval of $\dot{V}O_2max$ (MAS_{30s}) was determined, as this is another common definition for the determination of MAS (Buchheit, 2008; Sandford, Rogers, et al., 2019). The $\dot{V}O_2max$ was defined as the highest 30-s-interval of VO_2. The RER_{end} represented the highest value of the quotient VCO_2/VO_2 during the end of exercise. The HRmax was assessed using a chest strap (H7 or H10; Polar Electro; Kempele; Finland). In addition, RPE was queried after test termination. Immediately after the test, 20 µl of capillary blood was collected from the right earlobe and analyzed by the BIOSEN C-Line lactate analyzer (EKF Diagnostic; Barleben; Germany) to assess the maximal lactate value reached during the treadmill test (La_{end}). In order to achieve physical exhaustion and thus $\dot{V}O_2max$, the collected data were analyzed for the following exercise criteria, of which at least two had to be fulfilled (Neumann, 2013): $RER_{end} \geq 1.0$ (Dickhuth & Kindermann, 2002); RPE $\geq$ 17 (Sangan et al., 2021); HRmax $\geq$ 210-age, $La_{end} \geq 8$ mmol/L, and reaching a VO_2-plateau (Marées & Heck, 2003).

1500-m-Time Trial

To ensure reliability of the 1500-m-TT, subjects performed a habituation session one week in advance (Clarke et al., 2016). For HR measurement, each subject received a chest strap (H7 or H10; Polar Electro; Kempele; Finland). The subjects ran on a 400-m tartan track and performed a warm-up (at least 400 m jogging; 100 m easy acceleration runs; 3 min stretching) right before the start of the TT. During the TT, subjects were instructed to keep their speed as even as possible. The time to complete the 1500 m was measured with a stopwatch, from which the average speed in km/h (V_{1500m}) was determined (Darendeli et al., 2021). In addition, the regression equation of Bellenger et al. (2015) was used to calculate an approximation to the true MAS ($V_{calc}=V_{1500m}*(0.766+0.117*1.5 \text{ km})$). $HRmax_{1500m}$ and RPE_{1500m} were recorded after test termination to ensure physical exhaustion.

Statistical Analysis

Statistical analysis and creation of graphics were carried out with the statistical software IBM SPSS© Statistics (version 27). To detect possible differences between the parameters $MAS_{Plateau}$/ V_{UMTT}/ V_{1500m}/ V_{calc}, HRmax/ $HRmax_{UMTT}$/ $HRmax_{1500m}$, and RPE/ RPE_{UMTT}/ RPE_{1500m}, ANOVA with repeated measures and Bonferroni post-hoc tests were calculated. In addition, t-tests for dependent samples were used for the comparison of $MAS_{Plateau}$ vs. MAS_{30s}, and $MAS_{Plateau}$ vs. V_{calc}. The effect sizes of the ANOVA results were estimated by partial eta²: $0.01 \leq \eta_p^2 < 0.06$ is considered a small, $0.06 \leq \eta_p^2 < 0.14$ as a medium, and $0.14 \geq \eta_p^2$ as a large effect (Cohen, 1988). The effect sizes (ES) of the t-tests and post-hoc tests were calculated using Cohen's d: 0.2≤ES<0.5 represent small, 0.5≤ES<0.8 medium, and ES≥0.8 represent large effects (Cohen, 1988). Absolute agreement between $MAS_{Plateau}$, V_{UMTT}, and V_{1500m} and between $MAS_{Plateau}$ and MAS_{30s}, and $MAS_{Plateau}$ and V_{calc} was determined with the limits-of-agreement analysis (LoA analysis) and Bland-Altman plots (Altman & Bland, 1983). In addition, Pearson's correlation coefficient r and the intraclass correlation coefficient (ICC 3.1) were calculated. According to Hopkins (2004), the magnitude of the correlation was considered to be small (0.1≤r/ICC<0.3), medium (0.3≤r/ICC<0.5), large (0.5≤r/ICC<0.7), very large (0.7≤r/ICC<0.9), and almost perfect (r/ICC≥0.9) classifications. The significance level for all calculations was set at $p<0.05$.

5.1.4 Results

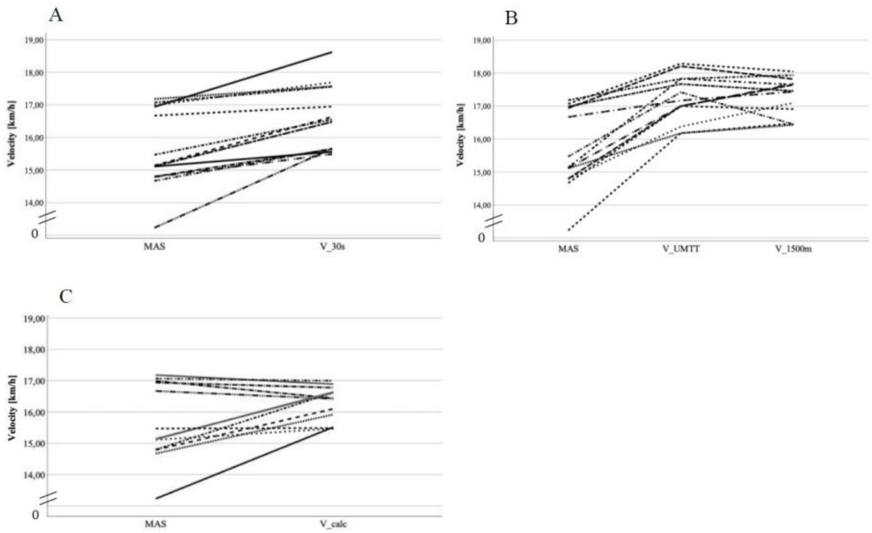

Figure 5.1: Spaghetti plots for intra- and interindividual comparison of A) $MAS_{Plateau}$ and MAS_{30s}; B) $MAS_{Plateau}$, V_{UMTT}, and V_{1500m}; and C) $MAS_{Plateau}$ and V_{calc}.

Each subject met three or more of the specified criteria, so that physical exhaustion was ensured. The mean values and standard deviations of the recorded parameters for the incremental treadmill test, UMTT and the 1500-m-TT are shown in Table 5.1. Moreover, individual progressions of $MAS_{Plateau}/MAS_{30s}$, $MAS_{Plateau}/V_{UMTT}/V_{1500m}$, and $MAS_{Plateau}/V_{calc}$ are visualized as spaghetti plots in Figure 5.1. These descriptive results already indicate an overestimation of $MAS_{Plateau}$ by the estimations, i.e., MAS_{30s}, V_{UMTT}, V_{1500m}, and V_{calc}.

Table 5.1: Descriptive results for the CPET on the treadmill, UMTT, and 1500-m-TT. Results are presented as mean values ± SD.

	MAS/V_{Test} [km/h]	**RPE [N/A]**	**HRmax [bpm]**	**$\dot{V}O_2max$ [ml/kg/min]**	**La_{end} [mmol/l]**	**RER_{end} [N/A]**
	mean ± SD					
CPET	$MAS_{Plateau}$: 15.63 ± 1.22 MAS_{30s}: 16.62 ± 1.01 V_{max}: 17.29 ± 1.07	19.38 ± 0.77	185.54 ± 7.67	49.92 ± 3.15	8.52 ± 2.81	1.18 ± 0.05
UMTT	V_{UMTT}: 17.24 ± 0.71	17.85 ± 1.21	186.85 ± 7.06	-	-	-
1500-m-TT	V_{1500m}: 17.31 ± 0.58 V_{calc}: 16.30 ± 0.54	17.77 ± 1.74	183.54 ± 6.65	-	-	-

SD – standard deviation, CPET – cardiopulmonary exercise testing; UMTT – Université de Montréal Track Test; 1500-m-TT – 1500-meters-time trial; MAS – maximal aerobic speed; V_{Test} – estimate of MAS by field tests; $MAS_{Plateau}$ – maximal aerobic speed assessed as velocity of onset of VO_2-plateau; MAS_{30s} – first velocity of 30-s-interval of $\dot{V}O_2max$; V_{max} – maximal speed achieved during CPET; V_{UMTT} – maximal velocity in UMTT; V_{1500m} – average velocity in 1500-m-TT; V_{calc} – velocity estimated by regression equation with final speed of 1500-m-TT (V_{1500m}*(0.766+0.117*1.5 km); Bellenger et al., 2015); RPE – ratings of perceived exertion; HRmax – maximal heart rate; $\dot{V}O_2max$ – maximal oxygen update; La_{end} – lactate value at test termination; RER_{end} – respiratory exchange ratio at test termination.

The comparison of both VO_2-kinetic based methods to assess MAS resulting in the parameters $MAS_{Plateau}$ and MAS_{30s} (see Table 5.2) shows a significant increase by 0.99 km/h ($p<0.01$) with a large effect (ES=1.61) and Limits of Agreement (LoA) ranging from -0.21–2.20 km/h (see Figure 5.2). Though, results of correlation analysis show very large correlations between $MAS_{Plateau}$ and MAS_{30s} ($r=0.87$; ICC=0.85; see Table 5.2).

Moreover, V_{UMTT} and V_{1500m} overestimate $MAS_{Plateau}$ by 1.61 km/h ($p<0.01$; ES=2.03) and 1.68 km/h ($p<0.01$; ES=1.77), respectively. Between V_{UMTT} and V_{1500m}, no significant difference ($p=0.99$; ES=0.14) was found. The LoA between V_{UMTT} and V_{1500m} range from -0.8–1.01 km/h, between $MAS_{Plateau}$ and V_{UMTT} from 0.05–3.17 km/h, and between

$MAS_{Plateau}$ and V_{1500m} from -0.18–3.55 km/h. The correlations between the three velocities are large to very large (0.65≤r≤0.79; p≤0.02; 0.51≤ICC≤0.72; p≤0.03). The comparison of $MAS_{Plateau}$ and V_{calc} shows a significant difference (MD = 0.67 km/h; p=0.03; ES=0.70). In addition, the LoA between $MAS_{Plateau}$ and V_{calc} range from -1.21–2.55 km/h. There is a medium to large correlation between $MAS_{Plateau}$ and V_{calc} (r=0.65; p=0.02; ICC=0.40; p=0.04).

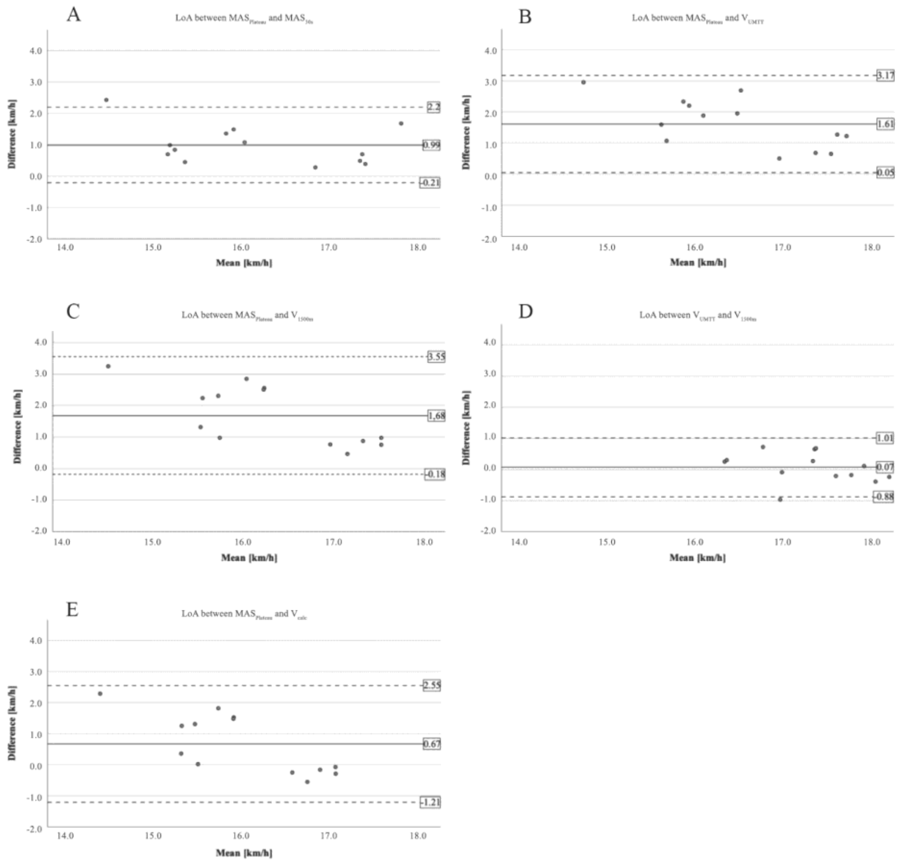

Figure 5.2: Bland-Altman plots for limits-of-agreement analysis (LoA analysis) between A) $MAS_{Plateau}$ and MAS_{30s}; B) $MAS_{Plateau}$ and V_{UMTT}; C) $MAS_{Plateau}$ andV_{1500m}; D) V_{UMTT} and V_{1500m}; and E) $MAS_{Plateau}$ and V_{calc}. The solid lines represent the mean difference, the dashed lines represent the limits of agreement (±1.96 SD

Table 5.2: Results of ANOVA, Bonferroni post-hoc tests, t-tests, and correlation analysis.

	MD (95 % CI)	**p**	**η_p^2**	**ES (95 % CI)**	**r (95 % CI)**	**p**	**ICC (95 % CI)**	**p**
$MAS_{Plateau}$/ MAS_{30s}	0.99 km/h (0.62–1.36)	< 0.01*	-	1.61 (0.76–2.43)	0.87 (0.60–0.96)	< 0.01*	0.85 (0.58–0.95)	< 0.01*
$MAS_{Plateau}$/ V_{calc}	0.67 km/h (0.09–1.25)	0.03*	-	0.70 (0.07–1.25)	0.65 (0.16–0.90)	0.02*	0.40 (-0.08–0.80)	0.04*
$MAS_{Plateau}$/ V_{UMTT}/ V_{1500m}	-	< 0.01*	0.77	-	-	-	0.62 (0.31–0.85)	< 0.01*
$MAS_{Plateau}$/ V_{UMTT}	1.61 km/h (1.00–2.23)	< 0.01*	-	2.03 (1.05–2.98)	0.79 (0.42–0.93)	< 0.01*	0.69 (0.24–0.89)	< 0.01*
$MAS_{Plateau}$/ V_{1500m}	1.68 km/h (0.95–2.42)	< 0.01*	-	1.77 (0.87–2.64)	0.65 (0.16–0.90)	0.02*	0.51 (-0.40–0.82)	0.03*
V_{UMTT}/ V_{1500m}	0.07 km/h (-0.30–0.44)	0.99	-	0.14 (-0.41–0.69)	0.74 (0.32–0.92)	< 0.01*	0.72 (0.31–0.91)	< 0.01*
HRmax/ $HRmax_{UMTT}$/ $HRmax_{1500m}$	-	0.09	0.18	-	-	-	0.73 (0.47–0.90)	< 0.01*
HRmax/ $HRmax_{UMTT}$	1.31 bpm (-1.83–4.45)	0.81	-	0.31 (-0.24–0.87)	0.85 (0.56–0.95)	< 0.01*	0.85 (0.58–0.95)	< 0.01*
HRmax/ $HRmax_{1500m}$	-2.00 bpm (-6.77–2.77)	0.80	-	0.32 (-0.24–0.88)	0.63 (0.13–0.88)	0.02*	0.63 (0.14–0.87)	< 0.01*
$HRmax_{UMTT}$/ $HRmax_{1500m}$	-3.31 bpm (-7.34–0.73)	0.13	-	0.63 (0.02–1.22)	0.71 (0.27–0.91)	< 0.01*	0.71 (0.29–0.90)	< 0.01*

	MD (95 % CI)	p	η_p^2	ES (95 % CI)	r (95 % CI)	p	ICC (95 % CI)	p
$RPE/ RPE_{UMTT}/ RPE_{1500m}$	-	< 0.01*	0.47	-	-	-	0.40 (0.06–0.73)	0.01*
RPE/ RPE_{UMTT}	-1.54 (-2.56–-0.51)	< 0.01*	-	1.16 (0.43–1.85)	0.16 (-0.43–0.65)	0.61	0.14 (-0.42–0.63)	0.31
RPE/ RPE_{1500m}	-1.62 (-2.73–-0.50)	< 0.01*	-	1.12 (0.40–1.80)	0.57 (0.03–0.85)	0.04*	0.42 (-0.14–0.78)	0.07
RPE_{UMTT}/ RPE_{1500m}	-0.08 (-1.23–1.08)	> 0.99	-	0.05 (-0.49–0.59)	0.53 (-0.02–0.84)	0.06	0.51 (-0.04–0.82)	0.03*

MD – mean difference; 95% CI – 95% Confidence Interval; p – significance level; * – $p < 0.05$, i.e., significant difference; η_p^2 – partial squared eta; ES – effect size of Bonferroni post-hoc tests and t-tests; r – Pearson's Coefficient of Correlation; ICC – Intra Class Correlation Coefficient; $MAS_{Plateau}$ – maximal aerobic speed assessed as velocity of onset of VO_2-plateau; MAS_{30s} – first velocity of 30-s-interval of $\dot{V}O_2max$; V_{UMTT} – maximal velocity in UMTT; V_{1500m} – average velocity in 1500-m-TT; V_{calc} – velocity estimated by regression equation with final speed of 1500-m-TT (V_{1500m}*(0.766+0.117*1.5 km); Bellenger et al., 2015); RPE – ratings of perceived exertion; HRmax – maximal heart rate.

5.1.5 Discussion

Main findings

The first aim of this study was to compare two different VO_2-kinetic based methods to determine MAS in soccer players, i.e., $MAS_{Plateau}$ and MAS_{30s}, using CPET on a treadmill. $MAS_{Plateau}$ was consistently overestimated by MAS_{30s}, nevertheless, $MAS_{Plateau}$ and MAS_{30s} were highly correlated.

The second aim was to investigate the convergent validity of the UMTT and a 1500-m-TT to estimate $MAS_{Plateau}$. $MAS_{Plateau}$ was overestimated by both V_{UMTT} and V_{1500m}, nonetheless, large to very large correlations with $MAS_{Plateau}$ were found. Further, the calculated speed from the 1500-m-TT according to Bellenger et al. (2015), V_{calc}, was significantly higher than $MAS_{Plateau}$.

Discussion of MAS assessment via CPET

The results of the CPET to determine MAS illustrate the difference between two of the common definitions of MAS. Since $\dot{V}O_2max$ in healthy subjects almost always occurs before the end of an physical exhaustion exercise and a VO_2-plateau by definition lasts at least one minute (Meyer & Kindermann, 1999), a significant difference between $MAS_{Plateau}$ and MAS_{30s} was expected. The mean difference of 0.99 km/h indicates that after reaching $MAS_{Plateau}$, subjects maintained their performance for an average of almost 1.5 min with a higher proportion of anaerobic resources until MAS_{30s} was reached (Buchheit, 2010). Because $MAS_{Plateau}$ represents the first velocity when reaching a VO_2-plateau (Di Prampero et al., 1986) and therefore reflects the maximal speed with mainly aerobic resources, efforts above the onset of the plateau are associated with a higher input of anaerobic resources. Hence, velocities above the onset of a VO_2-plateau should not be attributed as a MAS. The very large effect size illustrates the practical relevance of this difference and the very large correlation between the two velocities supports the consistent overestimation of $MAS_{Plateau}$. Therefore, MAS should be determined individually based on VO_2-kinetics by investigating the plateau. In addition, these results suggest that studies that used V_{max} (Berthoin et al., 1996) or MAS_{30s} (Sandford, Rogers, et al., 2019) to validate field testing procedures, probably did not use the "true" MAS determined by CPET with examining the onset of the VO_2-plateau as a gold standard, which may have biased the results.

Discussion of UMTT and 1500-m-TT

The LoA between $MAS_{Plateau}$ and V_{UMTT} indicate a wide dispersion of individual differences. Moreover, the significant overestimation found in this study is similar to the results of Lacour et al. (1991) who also reported a higher V_{UMTT} than MAS (+0.25 ± 0.07 km/h, $p = 0.03$) and a nearly perfect correlation ($r = 0.92$; $p < 0.01$) in a group of runners despite using a different protocol and a different definition for MAS. In contrast, Berthoin et al. (1996) and Souza et al. (2014) did not find differences between MAS and V_{UMTT}, but also used different protocols and definitions of MAS. Berthoin et al. (1996) determined the velocity of the last stage for both MAS (assessed by CPET on a treadmill) and V_{UMTT}, which means that they did not distinguish between MAS and V_{max}. On the contrary, in the present study, V_{UMTT} was compared to $MAS_{Plateau}$, which represents the first velocity of the VO_2-plateau. The UMTT represents an incremental test similar to CPET on a treadmill and because the final speed achieved during the UMTT is used as V_{UMTT} the significant difference to $MAS_{Plateau}$ assessed as the onset of a VO_2-plateau can be explained.

Additionally, V_{1500m} shows a systematic overestimation of $MAS_{Plateau}$. Nevertheless, both the relatively large LoA and the large 95% CI of the mean difference indicate interindividual discrepancies in the differences between $MAS_{Plateau}$ and V_{1500m}. Sandford et al. (2019) also detected an overestimation of MAS by V_{1500m}. The overestimation could be explained by the assumption that the distance for the total sample may have been too short to include only aerobic resources, but additionally anaerobic resources to run the 1500 m in the best possible time. The fact that for some players the V_{1500m} was considerably closer to the $MAS_{Plateau}$ than for others could indicate a heterogeneous character of the endurance performance of the sample. This may be due to the non-professional level of the sample on the one hand and on the other hand to position-specific differences. Different endurance profiles related to the player position could already be demonstrated in part (Altmann et al., 2020). Therefore, different distances should be used when implementing TT to estimate $MAS_{Plateau}$ depending on the endurance performance level.

To address this issue, Bellenger et al. (2015) propose a regression equation (V_{calc}) to estimate MAS by set distance TT with distances between 1600 m and 2200 m. The comparison of $MAS_{Plateau}$ and V_{calc} shows similar results as the comparison of $MAS_{Plateau}$ and V_{1500m}. In this sense, V_{calc} also overestimates $MAS_{Plateau}$. If individual variations are considered, it is plausible that, as with $V_{1500m,}$ the dispersion around the mean difference is very large. This was to be expected, since V_{calc} is calculated from V_{1500m}. The individual differences were merely shifted downward, so that they scatter both to the positive and to the negative. However, it should be noted that the regression equation used to calculate V_{calc} was set up by Bellenger et al. (2015) using V_{UMTT} as reference. This could additionally explain the overestimation of the $MAS_{Plateau}$ in this study.

Moreover, the comparison of the two velocities V_{1500m} and V_{UMTT} achieved during the field test have the lowest mean difference and narrowest range of variation, as well as a very large correlation. Both Bellenger et al. (2015) and Lundquist et al. (2021) found high to very high levels of agreement between V_{1400m}–V_{2000m} and V_{UMTT} in male and female Australian Rules Football players. This also indicates a similar intensity of the two test procedures for team sports athletes.

Delimitations and limitations

The gold standard method to assess MAS has not yet been clarified, in particular it is unclear which treadmill protocol leads to the "true" MAS, especially in soccer. A major delimitation of our study is that we used a protocol with a 0.5 min break between the stages, which commonly serves to measure lactate via capillary blood between the stages of an incremental treadmill test. When analysing the individual VO_2-kinetics, we determined that the break between the stages is a major limitation. This pause probably allowed a short recovery, so that VO_2 progression delayed, especially at higher speeds at the beginning of a stage. This influences individual determination of MAS based on the VO_2-kinetics and possibly postpones physical exhaustion and thus reaching $\dot{V}O_2max$ (Metaxas et al., 2005). As a further delimitation, different environmental conditions may have influenced performance during the different test procedures. For example, some players completed the incremental treadmill test in the morning or at noon, with the UMTT and 1500-m-TT occurring in the evening for all subjects. Changes in performance at different times of the day have already been confirmed (Chtourou & Souissi, 2012). A limitation of our study is that the field tests were performed in different groups while the treadmill test was performed individually. This might have induced different levels of motivation in the subjects at the test time points. A last point to consider is the relatively heterogeneous aerobic endurance performance of the subjects. The $MAS_{Plateau}$ of the sample shows a range of 13.23-17.18 km/h. Due to heterogeneous performance, the use of a TT with the same distance for all subjects is questionable. However, a habituation session was performed for improvement of independent speed control during the 1500-m-TT.

Future research

In order to interpret and compare different study results, it is important to use a consistent gold standard method for the assessment of MAS. Since different definitions are used to determine MAS, future research is necessary to clearly delineate $MAS_{Plateau}$, MAS_{30s} and V_{max}. Because previous studies on the validity of field test procedures have not been conducted with a uniform gold standard method and because MAS determination via an incremental treadmill test claims many resources, further investigation of the validity of existing field test procedures or the development of new test procedures is essential. Especially in team sports and its divergent endurance performance levels, there is a great potential for research in this regard. Regarding a TT, e.g., a classification of players into different endurance profiles based on norm values of MAS or by different expressions of anaerobic speed reserve (Sandford et al., 2021) and the assignment of these levels to appropriate distances to estimate MAS should be investigated in the future. Thus, a more accurate estimate of MAS using a TT would be possible. Though, the sample consisted of trained soccer players, the results can not directly be transferred to professional soccer. Therefore, more research regarding the assessment of MAS is required with professional soccer players.

In addition, technological evolutions may simplify MAS estimation in the future. On the one hand, global positioning systems could make it easier and presumably more accurate to record velocities in field tests, and on the other hand, algorithms could be developed and validated that estimate the current MAS based on certain physiological parameters - at best during training - and indicate any acute adjustments (Leser et al., 2011). Given the tight schedules of soccer players and coaches, integrating physiological diagnostics into the usual training could lead to a more efficient time schedules of players and coaches.

Practical applications

The UMTT and 1500-m-TT do not appear to be valid and thus less appropriate methods for estimating MAS for male soccer players. The LoA for both, UMTT and 1500-m-TT, indicate the deviations from MAS are higher than typical improvements of MAS achieved through specific training programs (Denadai et al., 2006; González-Mohíno et al., 2016). Therefore, training based on MAS estimations via UMTT or a TT might lead to much higher intensities than expected when using the true MAS, probably resulting in less improvements in performance, overload, or even a higher risk of injuries. For this purpose, it is recommended to either set up regression equations using a consistent gold standard method for estimating MAS using the V_{UMTT} or V_{1500m} or to choose individual distances for TT adjusted to the endurance performance level. Moreover, adapted training programs are possible, when the individual intensity of V_{UMTT} or V_{1500m} in deviation to MAS is known.

5.1.6 Conclusion

To conclude, our results indicate that different definitions of MAS lead to different results and that estimates by field tests are non-appropriate methods to determine MAS in trained soccer players. Conversely, using such methods may result in researchers and practitioners using too high intensities. This indicates the necessity of MAS-assessment by investigating VO_2-kinetics and examining the onset of the VO_2-plateau or the use of adjusted or new field tests to estimate MAS. This work provides the first evidence on the validity of MAS estimation of different field tests in soccer players. To improve MAS estimation in field tests, further valid and time saving methods as well as practical instructions for coaches should be developed in soccer in the future.

5.2 Systematic Review on the Validity and Reliability of Methods to Determine the Locomotor Profile (Paper III)

Published as:

Thron, M., Dueking, P., Ruf, L., Haertel, S., Woll, A., & Altmann, S. (2024). Assessing Anaerobic Speed Reserve: A Systematic Review on the Validity and Reliability of Methods to Determine Maximal Aerobic Speed and Maximal Sprinting Speed in Running-based Sports. PLoS ONE, 19. https://doi.org/10.1371/journal.pone.0296866

5.2.1 Abstract

Purpose. Locomotor profiling using anaerobic speed reserve (ASR) enables insights into athletes' physiological and neuromuscular contributing factors and prescription of high-intensity training beyond maximal aerobic speed (MAS). This systematic review aimed to determine the validity and reliability of different methods to assess the characteristics of ASR, i.e., MAS and maximal sprinting speed (MSS). **Methods.** A comprehensive search of the PubMed and Web of Science databases was conducted according to the PRISMA guidelines. Studies were included if they reported data on validity and/or reliability for methods to assess MAS or MSS. **Results.** 58 studies were included with 28 studies referring to MAS and 30 studies to MSS. Regarding MAS, different methods for cardiopulmonary exercise testing yielded different values (four out of seven studies) of MAS (Cohen's d (ES)=0.83–2.8; Pearson's r/intraclass correlation coefficient (r/ICC)=0.46–0.85). Criterion validity of different field tests showed heterogeneous results (ES=0–3.57; r/ICC=0.40–0.96). Intraday and interday reliability was mostly acceptable for the investigated methods (ICC/r>0.76; CV<16.9%). Regarding MSS, radar and laser measurements (one out of one studies), timing gates (two out of two studies), and video analysis showed mostly good criterion validity (two out of two studies) (ES=0.02–0.53; r/ICC=0.93–0.98) and reliability (r/ICC>0.83; CV<2.43%). Criterion validity (ES=0.02–7.11) and reliability (r/ICC=0.14–0.97; CV=0.7–9.77%) for global or local positioning systems (seven out of nine studies) and treadmill sprinting (one out of one studies) was not acceptable in most studies. **Conclusion.** The criterion validity of incremental field tests or shuttle runs to examine MAS cannot be confirmed. Results on time trials indicate that distances adapted to the participants' sporting background, fitness, or sex might be suitable to estimate MAS. Regarding MSS, only sprints with radar or laser measures, timing gates, or video analysis provide valid and reliable results for linear sprints of 20 to 70 m.

5.2.2 Introduction

Assessing athletic performance is often performed in sports science and sports practice, e.g. to individualize training procedures. In a variety of team and individual sports and at different performance levels, endurance testing is a required and inevitably part of the training routine, more specifically to set training intensities (Sandford et al., 2021).

Most currently used markers for endurance testing (e.g., lactate thresholds, maximal oxygen uptake ($\dot{V}O_2max$), critical speed) are limited to aerobic performance measures and therefore not applicable for the prescription of training in more intense exercise domains, e.g. intensities above $\dot{V}O_2max$ (Jamnick et al., 2020). For this purpose, the anaerobic speed reserve (ASR) as the difference between maximal sprinting speed (MSS) and maximal aerobic speed (MAS) can be used to profile athletes in running type sports on a physiological (referred to MAS) and neuromuscular (referred to MSS) basis and to prescribe training intensities (Sandford, Allen, et al., 2019; Sandford et al., 2021). By using proportions of ASR, exercise intensity beyond MAS can be set by normalizing absolute values of MAS and MSS that allows coaches or researchers to consider the individual tolerance to high-intensity exercise of an athlete (Blondel et al., 2001). Furthermore, ASR can be used to identify athletes with similar or different characteristics. For example, most team sports require more focus on MSS and thus a higher ASR compared to longer distance events in endurance sports that mostly require a higher MAS and thus lower ASR (Sandford et al., 2021). However within the same discipline, e.g. in track and field, ASR can differentiate into elite and sub-elite which was indicated by a strong relationship of ASR with 800-m running performance in world class middle-distance runners (Sandford, Allen, et al., 2019).

To assess ASR, i.e., MAS and MSS, different methods are used that can lead to different results and thus, e.g., different training prescriptions and subsequently adaptations to training (Hanley & Shaw, 2022). Cardiopulmonary exercise testing (CPET) including breathing gas analysis on a treadmill while employing an incremental protocol is considered as gold standard methodology to assess MAS (Billat et al., 1996; Riboli et al., 2017). MAS can be defined as the first speed associated with $\dot{V}O_2max$ (Billat & Koralsztein, 1996; Di Prampero et al., 1986), yet there is current debate about the exact procedure on how to define this speed. Di Prampero et al. (1986) first defined the MAS as a calculated speed based on the ratio of the maximal fraction of $\dot{V}O_2max$ and the energy cost of running, intended to describe the speed that a runner can sustain under aerobic conditions. Following, further definitions of MAS emerged as for example the speed at the onset of the VO_2-plateau and therefore the maximal speed where mainly aerobic resources are used (Buchheit, 2010; Thron, Woll, et al., 2022), the first speed associated with the 30-s interval of $\dot{V}O_2max$ (Sandford, Rogers, et al., 2019; Sangan et al., 2021), or as the maximal speed reached during the incremental treadmill test (Čović et al., 2016). Although even for CPET as the gold standard method different definitions of MAS are used, several field tests are currently implemented to estimate MAS. These range from incremental continuous field tests like the Université the Montréal Track Test (UMTT) or incremental shuttle runs to (set distance) time trials. Consequently, for MAS it is currently unclear which testing profile and which definition of the first speed when reaching $\dot{V}O_2max$ is the most valid and reliable.

Regarding MSS, linear sprint tests of 20–50 m with radar or laser measurement are mostly used as gold standard methods (Beato et al., 2018; Lacome et al., 2019; Ortiz et al., 2018; Simperingham et al., 2019). However, timing gates with 5- or 10-m split times or Global and Local Positioning Systems (GPS, LPS) are also very common methods. Moreover, GPS and LPS are implemented during matches or training (e.g. small-sided games) mainly in soccer to assess MSS (Djaoui et al., 2017).

Since the prescription of high-intensity training and the profiling of athletes based on ASR relies on valid and reliable testing of MAS and MSS to guarantee that any changes are not the result of measurement error (i.e., systematic and random error stemming from technological and biological sources) or intraindividual variances, the selection of measures needs to be carefully considered (Simperingham et al., 2016). While previous reviews focused for example on several influencing factors of sprint performance testing (such as temperature, wind, running surface or shoes) (Haugen & Buchheit, 2016) or aerobic fitness tests to assess $\dot{V}O_2max$ and often focused on only one type of sports (Bok & Foster, 2021), there exists no overview on the validity and reliability of testing methods for MAS and MSS in running-based sports.

Therefore, this review aims to systematically review the available literature on the validity and reliability of different methods to assess the two sub-components of ASR, i.e., MAS and MSS, in running-based sports, e.g., team sports, track and field, and runners at recreational and higher level. The results of this review can be of value for practitioners and scientists to choose the testing methodology that best meets their requirements.

5.2.3 Methods

This systematic review was written according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; see PRISMA 2020 checklist in Appendix 1 Paper III Supplementary Table 1) guidelines (Page et al., 2021)and no protocol was registered previously.

Eligibility criteria for included studies

To be included in the systematic review, the scientifically peer-reviewed publications had to meet the Patient, Intervention, Comparator, Outcome, and Study (PICOS) criteria (comparator criteria not applicable). Our search was limited to original articles published in peer-reviewed journals and written in English. References cited by the articles retrieved were also examined for potential relevance. Conference abstracts, dissertations, theses, and other non-peer-reviewed articles were excluded. Figure 5.3 illustrates the screening and selection process employed.

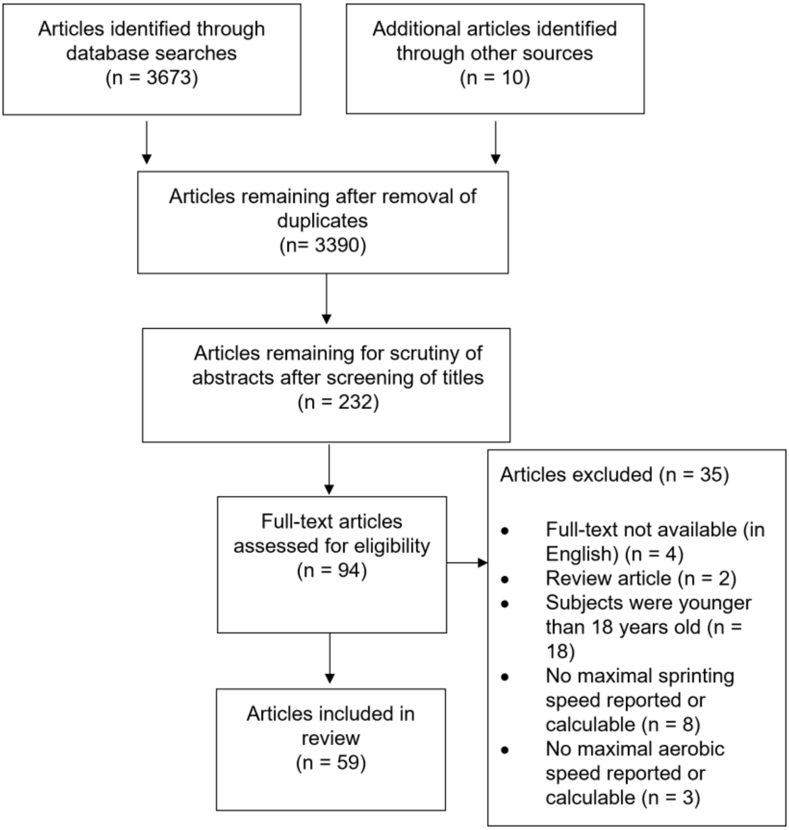

Figure 5.3: Selection of the articles to be analyzed, from initial identification to inclusion (Page et al., 2021).

Patients: All articles reporting on healthy active adults related to running with no restrictions on sex were included.

Intervention: Studies were included if they specifically evaluated methods to assess MAS and/or MSS. Eligibility criteria for study inclusion consisted of one of the following: (i) tests performed two or more times during one occasion (intraday reliability) or on two or more separate occasions (interday reliability); (ii) compared against other methods (criterion and convergent validity).

Outcome: All outcomes reporting validity and/or reliability of methods to assess MAS and/or MSS were included. If only split times during sprint tests were specified, the speed was calculated based on the time and distance by the authors of the present systematic review.

Study **Design**: Any original comparative studies were included.

Search strategy

A comprehensive search strategy was designed by the authors of this article. The electronic databases searched in August 2022 included PubMed and Web of Science (with no restriction concerning publication date) with an updated search being conducted in December 2022. The search strategy is illustrated using the search terms entered the PubMed database as example (Appendix 2 Paper III Supplementary Information 1) and was modified according to the indexing systems of Web of Science.

The following keywords were used to capture validity: validity, logical, criterion, convergent, discrimination, gold standard, level, standard. The following keywords were used to capture reliability: reliability, repeatability, reproducibility, measurement error, consistency, smallest worthwhile change, minimal detectable change, typical error, usefulness, sensitivity, relationship, relation, association, correlation. The following keywords were used to capture MAS: maximal aerobic speed, maximal aerobic velocity, MAS, velocity at $\dot{V}O_2max$, velocity associated with $\dot{V}O_2max$, $v\dot{V}O_2max$. The following keywords were used to capture MSS: maximal sprinting speed, maximal speed, MSS, maximal velocity, peak speed. The following keywords were used to capture ASR: anaerobic speed reserve, anaerobic velocity reserve, ASR.

Selection of studies

The identified articles were incorporated into the systematic review online tool Rayyan (rayyan.ai) where duplicates were eliminated. As previously performed and suggested (Page et al., 2021; Thron, Düking, et al., 2022), one of the authors (MT) examined the titles and abstracts of all possibly pertinent papers for eligibility, with independent verification by a second author (SA). The full texts of articles that met the criteria for inclusion were then retrieved and screened. When disagreements between reviewers arose, consensus was achieved through discussion or input from a third author (PD).

Data extraction and analysis

From the selected articles, one author (MT) extracted data which was independently confirmed by another (SA) and difficulties were resolved through discussion with the other authors. Extracted information concerned: details of publication, number of participants, demographic information (including sex, age, type of sports), testing methods with a short test description, reliability and validity type, outcome measures as well as results for validity or reliability, and the information required to assess the methodological quality of each study.

If possible, the mean difference, percentage difference and the respective effect sizes (ES as Cohen's d) between values of MAS or MSS from different methods or for different sampling time points were retrieved from the studies or calculated manually. ES (Cohen's d) was rated according to Cohen (1988): less than 0.2 was considered a trivial effect, $0.2 \leq ES < 0.5$ small effect, $0.5 \leq ES < 0.8$ moderate effect, and $ES \geq 0.8$ large effect. Values for the intraclass correlation coefficient (ICC), Pearson's r and the coefficient of variation (CV) were taken for reliability (both intraday and interday) and validity. CV is a measurement of absolute reliability and validity, whereas ICC and Pearson's r are indicators of relative reliability and validity. According to Hopkins (2004) the magnitude of the correlation was considered to be small ($0.1 \leq r/ICC < 0.3$), medium ($0.3 \leq r/ICC < 0.5$), large ($0.5 \leq r/ICC < 0.7$), very large ($0.7 \leq r/ICC < 0.9$), and almost perfect ($r/ICC \geq 0.9$) classifications. The CV was interpreted in relation to each other (Altmann et al., 2019). The analysis of the results was done descriptively.

Assessment of methodological quality

Based on the recommendation of Ma et al. (2020), the methodological quality of the studies included in this review was assessed through the COnsensus-based Standards for the selection of health Measurement INstruments (COSMIN) checklist by using the boxes for reliability, measurement error, criterion validity, and convergent validity (Mokkink et al., 2020; Mokkink et al., 2018). The risk of bias was assessed independently by two of the authors (PD & MT), with any disagreements again being resolved by consensus or through discussion with a third author (LR) (Buchheit, 2008).

The score for each item was determined as follows: 3 = *very good*; 2 = *adequate*; 1 = *doubtful*; 0 = *inadequate*, and NA = *not applicable*. The quality of each study was rated with a worst-score-count method to determine the risk of bias (Mokkink et al., 2018). Further evaluation of the methods' validity (i.e., criterion validity) and recommendations for practical application were based on the studies using an accepted gold-standard method (i.e., CPET for MAS; radar or laser for MSS) and achieving a methodological quality score of at least 2 (*adequate)*.

5.2.4 Results

Study results and overview of study characteristics

Of the 93 articles initially identified, 58 fulfilled all the criteria for inclusion in the analysis. Of the 28 articles reporting MAS, 23 referred to validity only (Barbero-Alvarez et al., 2015; Bellenger et al., 2015; Bernard et al., 2000; Berthoin et al., 1996; Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Billat et al., 1996; Carminatti et al., 2013; Da Silva & Machado, 2015; Darendeli et al., 2021; Dillon et al., 2021; Dittrich et al., 2011; Foster et al., 2022; Lacour et al., 1991; Lopes et al., 2015; Lorenzen et al., 2009; Lundquist et al., 2021; Pallarés et al., 2019; Paradisis et al., 2014; Riboli et al., 2017; Riboli et al., 2022; Sandford, Rogers, et al., 2019; Thron, Woll, et al., 2022) and five articles to both validity and reliability (Benhammou et al., 2021; Cappa et al., 2014; Čović et al., 2016; Sangan et al., 2021; Schnitzler et al., 2010). Regarding MSS, 30 studies were included from which 12 studies reported only validity (Barbero-Álvarez et al., 2010; Clark et al., 2019; Djaoui et al., 2017; Ferro et al., 2014; Fleureau et al., 2020; Lacome et al., 2019; Massard et al., 2018; Morin & Sève, 2011; Ogris et al., 2012; Roe et al., 2017; Vescovi, 2012; Young et al., 2008), two only reliability (Helland et al., 2019; Simperingham et al., 2019) and 16 both reliability and validity (Akyildiz et al., 2022; Beato & de Keijzer, 2019; Beato et al., 2018; Chahal et al., 2022; Coutts & Duffield, 2010; Fornasier-Santos et al., 2022; Ghigiarelli et al., 2022; Highton et al., 2012; Hoppe et al., 2018; Johnston et al., 2014; Johnston et al., 2012; Romero-Franco et al., 2017; Sagiroglu et al., 2021; Willmott et al., 2019; Zabaloy, Freitas, et al., 2021; Zabaloy, Giráldez, et al., 2021).

An overview of the study characteristics, including populations' characteristics, a short description of testing methods, reliability/validity type, and main results is given in Table 5.3 for MAS and in Table 5.4 for MSS. Additionally, Table 5.5 presents a descriptive overview of the participants' age, the contribution of sexes, and the sporting background.

Table 5.3: Overview of study characteristics and results on the assessment of maximal aerobic speed.

Study	**Population**				**Short description**	**Type**	**Results**	**MQ**
	N	Sex	Age [years]	Description				
Barbero-Alvarez et al. (2015)	14	Female	21.1 ± 4.0	National team futsal players	CPET on treadmill (protocol: 6-2-3; MAS_{calc}: linear function of $\dot{V}O_2max$); Futsal-specific shuttle running test (3 x 15 m with increasing velocities and 10 or 30 s rest; $V_{ShuttleTest}$: peak velocity)	Criterion validity	*Validity*: MAS_{calc} and $V_{ShuttleTest}$: MD=2.7 km/h (+21.6%); ES=2.04; r=0.85	1
Bellenger et al. (2015)	28	Male	19.8 ± 2.6	Australian rules football players	UMTT (protocol: 10-1-2; V_{UMTT}: maximal velocity); 1.2-km TT ($V_{1.2km}$: average velocity); 1.4-km TT ($V_{1.4km}$: average velocity); 1.6-km TT ($V_{1.6km}$: average velocity); 1.8-km TT ($V_{1.8km}$: average velocity); 2.0-km TT ($V_{2.0km}$: average velocity); 2.2-km TT ($V_{2.2km}$: average velocity)	Convergent validity	*Validity*: V_{UMTT} and $V_{1200\text{-}m}$: MD=1.55 km/h (+9.4%); ES=2.08; r=0.70 V_{UMTT} and $V_{1400\text{-}m}$: MD=1.32 km/h (+7.4%); ES=1.43; r=0.85 V_{UMTT} and $V_{1600\text{-}m}$: MD=0.45 km/h (+3.5%); ES=0.82; r=0.69 V_{UMTT} and $V_{1800\text{-}m}$: MD=0.33 km/h (+1.5%); ES=0.29; r=0.81 V_{UMTT} and $V_{2000\text{-}m}$: MD=0.01 km/h (+0.8%); ES=0.17; r=0.79 V_{UMTT} and $V_{2200\text{-}m}$: MD=-0.29 km/h (-1.8%); ES=0.33; r=0.82	3

Benhammou et al. (2021)	43	Male	18.2 ± 2.2	Healthy adults of different fitness levels	VAM-EVAL (protocol: 8.5-0.5-1; V_{VAM}: peak velocity); $Test_{3L}$ (3/5/7 x running greatest possible distance for 1 minute; depends on fitness level; 30 s active rest; V_{3L}: total distance/58 (or 91 or 124; depends on level)	Convergent validity; Interday reliability	*Validity*: Beginners: V_{VAM} and V_{3L}: MD=-0.2 km/h (-1.4%); ES=0.42; r=0.27 Trained: V_{VAM} and V_{3L}: MD=-0.4 km/h (-2.4%); ES=0.60; r=-0.68 Elite: V_{VAM} and V_{3L}: MD=0.2 km/h (+1.0%); ES=0.30; r=0.28 All: V_{VAM} and V_{3L}: MD=-0.3 km/h (-1.9%); ES=0.12; r=0.93 *Reliability*: Beginners: V_{3L}: MD=0.0 km/h (0%); ES=0.00; ICC=0.96; r=0.97; CV=5.0 % Trained: V_{3L}: MD=0.0 km/h (0%); ES=0.00; ICC=0.85; r=0.87; CV=2.6 % Elite: V_{3L}: MD=-0.1 km/h (-0.5%); ES=0.13; ICC=0.98; r=0.99; CV=3.7 % All: V_{3L}: MD=0.1 km/h (0.6%); ES=0.04; ICC=0.99; r=0.99; CV=16.9%	3 3
Bernard et al. (2000)	13	Male	26.0 ± 6.0	Healthy adults	CPET on treadmill: three square-wave tests at speeds differing by 0.5 km/h (highest velocity was based on MAS_{30s} measured with an incremental treadmill test; lowest velocity was MAS_{30s} minus 4 km/h; MAS_4: extrapolated of VO_2 at the end of 4th minute; MAS_6: extrapolated of VO_2 at the end of 6th minute; MAS_{SS}: extrapolated from steady-state VO_2)	Criterion validity	*Validity*: MAS_{SS} and MAS_6: MD=0.24 km/h (+1.3%); ES=0.30; r=0.98 MAS_{SS} and MAS_4: MD=0.84 km/h (+4.6%); ES=1.11; r=0.85 MAS_6 and MAS_4: MD=0.60 km/h (+3.3%); ES=0.83; r=0.87	1

Berthoin et al. (1996)	11	Male	22.2 ± 3.0	Physical education students	CPET on treadmill (4 % incline; protocol: 10-2-4; MAS_{max}: velocity of last stage; MAS_{calc}: ($\dot{V}O_2max$-0.083)/energy cost (44); MAS_{ex}: extrapolated from VO_2 at each velocity (93); UMTT (protocol: 10-1-2; V_{UMTT}: velocity of last stage)	Criterion validity	*Validity*: MAS_{max} and MAS_{calc}: MD=-0.15 km/h (-0.8%); ES=0.06, r=0.99 MAS_{max} and MAS_{ex}: MD=-0.47 km/h (-2.8%); ES=0.21; r=0.93 MAS_{max} and V_{UMTT}: MD=-0.40 km/h (-2.3%); ES=0.19; r=0.96 MAS_{calc} and MAS_{ex}: MD=-0.32 km/h (-1.9%); ES=0.20; r=0.92 MAS_{calc} and V_{UMTT}: MD=-0.25 km/h (-1.5%); ES=0.17; r=0.96 MAS_{ex} and V_{UMTT}: MD=0.10 km/h (+0.4%); ES=0.05; r=0.85	**1**
Berthon et al. (1997)	48	Male	27.9 ± 6.9	Healthy adults of different fitness levels	CPET on treadmill (1 % incline; protocol: 70 % of theoretical HRmax-1.5-3; MAS_{max}: maximal velocity); UMTT (protocol: 6.4-0.3-0.5; V_{UMTT}: maximal velocity); 5-min TT (V_{5min}: average velocity)	Criterion validity	*Validity*: MAS_{max} and V_{UMTT}: MD=1.4 km/h (+8.3%); ES=0.54; r=0.95 MAS_{max} and V_{5min}: MD=0.3 km/h (+1.8%); ES=0.08; r=0.94	3
Berthon et al. (1997)	18 23	Male	Sub-elite runners: 28.7 ± 6.9; Non-running sportsmen: 23.9 ± 5.0	Sub-elite runners; non-running sportsmen	CPET on treadmill (1 % incline; protocol: 70 % of theoretical HRmax-1.5-3; MAS_{max}: maximal velocity); 5-min TT (V_{5min}: average velocity)	Criterion validity	*Validity*: Sub-elite runners: MAS_{max} and V_{5min}: MD=0.1 km/h (+0.5%); ES=0.11; r=0.86 Non-running sportsmen: MAS_{max} and V_{5min}: MD=0.2 km/h (+1.3%); ES=0.17; r=0.84	3

Billat et al. (1996)	15	Male	24.0 ± 2.0	Endurance trained athletes	CPET on treadmill (protocol 1: 15-1-2; protocol 2: 15-0.5-1; MAS_1/MAS_2: velocity when $\dot{V}O_2max$ occurred as long as velocity was sustained for at least 1 min; if not, then velocity of previous stage was taken); UMTT (protocol: 10-1-2; V_{UMTT}: velocity of the last stage)	Criterion validity	*Validity*: MAS_1 and MAS_2: MD=0.1 km/h (+0.5%); ES=0.11; r=0.8 MAS_1 and V_{UMTT}: MD=-1.0 km/h (-4.7%); ES=1.43; r=0.6	3
Cappa et al. (2014)	14	Male	25.5 ± 3.2	Physical education students	CPET on treadmill (protocol: 8 km/h for 3 min, then 10 km/h for 2 min, then 11-1-1; $MAS_{\dot{V}O_2max}$: lowest speed at which $\dot{V}O_2max$ was reached); UNCa Test (hexagon of 20-meter-long sides; protocol: 8 km/h for 3 min, then 10 km/h for 2 min, then 11-1-1; V_{UNCa}: speed of the last stage)	Criterion validity; Interday reliability	*Validity*: $MAS_{\dot{V}O_2max}$ and V_{UNCa}: MD=-2.0 km/h (12.8%); ES=1.9; r=0.83 *Reliability:* $MAS_{\dot{V}O_2max}$: MD=-0.1 km/h (-0.7%); ES=0.11; r=0.87	3 1
Carminatti et al. (2013)	18	Male	21.9 ± 2.0	Physical education students	VAM-EVAL (protocol: 8.5-0.5-1; V_{VAM}: peak velocity); CAR test (protocol: 9-0.6-1.5; 6 s active break; V_{CAR}: speed of the last stage)	Convergent validity	*Validity*: V_{VAM} and V_{CAR}: MD=0.1 km/h (+0.6%); ES=0.08; r=0.98	3
Čović et al. (2016)	17	Female	22.8 ± 4.3	Elite soccer players	CPET on treadmill (1.8° incline; protocol: 3 km/h for 3 min, then 7-1-1; MAS_{max}: velocity of last stage); 30-15 IFT (protocol: 8-0.5-0.5; 15 s passive break; V_{IFT}: velocity of last completed stage)	Criterion validity; Interday reliability	*Validity*: MAS_{max} and V_{IFT}: MD=4.0 km/h (+29.5%); ES=0.98; r=0.57 *Reliability*: V_{IFT}: MD=0.3 km/h (+1.6%); ES=0.29; ICC=0.91; CV=1.8 %	3 3

Da Silva and Machado (2015)	21	Male	41.2 ± 6.9	Amateur runners	CPET on treadmill (protocol: 7 km/h for 3 min; then 9-1-3; $MAS_{\dot{V}O_2max}$: speed in which $\dot{V}O_2$max was observed; MAS_{ex}: extrapolated from VO_2 at each velocity (94); MAS_{calc1}: $\dot{V}O_2$max/energy cost of running (8); MAS_{calc2}: ($\dot{V}O_2$max-VO_2rest)/energy cost of running (44); MAS_{max}: velocity of last stage)	Criterion validity	*Validity*: MAS_{max} and $MAS_{\dot{V}O_2max}$: MD=-0.1 km/h (-0.7%); ES=0.07; r=0.94 MAS_{max} and MAS_{calc1}: MD=-0.1 km/h (-0.7%); ES=0.06; r=0.91 MAS_{max} and MAS_{ex}: MD=-0.4 km/h (-2.6%); ES=0.27; r=0.93 MAS_{max} and MAS_{calc2}: MD=0.3 km/h (+2.0%); ES=0.19; r=0.91 $MAS_{\dot{V}O_2max}$ and MAS_{calc1}: MD=0.0 km/h (0%); ES=0.00; r=0.86 $MAS_{\dot{V}O_2max}$ and MAS_{ex}: MD=-0.3 km/h (-2.0%); ES=0.19; r=0.90 $MAS_{\dot{V}O_2max}$ and MAS_{calc2}: MD=0.4 km/h (+2.6%); ES=0.25; r=0.85 MAS_{calc1} and MAS_{ex}: MD=-0.3 km/h (-2.0%); ES=0.18; r=0.92 MAS_{calc1} and MAS_{calc2}: MD=0.4 km/h (+2.6%); ES=0.24; r=1.00 MAS_{ex} and MAS_{calc2}: MD=0.7 km/h (+4.7%); ES=0.42; r=0.92	3
Darendeli et al. (2021)	18	Male	18.3 ± 0.5	Amateur soccer players	UMTT (protocol; 10-1-2; V_{UMTT}: speed of the last stage); YoYo-IRT 1 (protocol: starting at 10 km/h 40-m shuttles with 10-s active break; $V_{YoYo-IRT1}$: final speed; $V_{YoYo-IRT1CALC}$: 0.701*distance covered+0.03*(height in cm-2.201 (95)); 20-m ST (20-m shuttles; protocol: 8.5-0.5-1; $V_{20mST:}$: final speed; $V_{20mSTCALC}$: V_{20mST} *1.81-7.86) (96)); 5-min TT (V_{5min}: average velocity)	Convergent validity	*Validity*: V_{UMTT} and $V_{YoYo-IRT1}$: MD=1.6 km/h (+10.5%); ES=1.60; r=0.69 V_{UMTT} and $V_{YoYo-IRT1CALC}$: MD=1.0 km/h (+6.5%); ES=0.72; r=0.63 V_{UMTT} and $V_{20mST:}$: MD=-2.1 km/h (-13.3%); ES=2.21; r=0.70 V_{UMTT} and $V_{20mSTCALC}$: MD=0.8 km/h (+5.2%); ES=0.60; r=0.8 V_{UMTT} and V_{5min}: MD=0.5 km/h (+3.3%); ES=0.45; r=0.52	3

Dillon et al. (2021)	29	Male	NA	Australian Rules Football	30-15 IFT (protocol: 8-0.5-0.5; 15 s passive break; 80% V_{IFT}: 80 % of velocity of last completed stage); 3-km TT (V_{3km}: average velocity during the 3 km; V_{500m}: average velocity during the fastest 500-m split; V_{1000m}: average velocity during the fastest 1000-m split)	Convergent validity	*Validity*: 80% V_{IFT} and V_{3km}: MD=-0.07 km/h (-0.3%); ES=0.09; r=0.72 80% V_{IFT} and V_{500m}: MD=1.37 km/h (+8.1%); ES=1.65; r=0.74 80% V_{IFT} and V_{1000m}: MD=1.12 km/h (6.6%); ES=1.38; r=0.75	3
Dittrich et al. (2011)	30	Male	23.3 ± 4.1	Professional soccer and futsal players	CPET on treadmill (1% incline; protocol: 9-1.2-3 with 0.5 min breaks; MAS_{1min}: first speed where $\dot{V}O_2max$ occurred and maintained for at least 1 min); CAR test (protocol: 9-0.6-1.5; 6 s active break; V_{CAR}: speed of the last stage)	Criterion validity	*Validity*: MAS_{1min} and V_{CAR}: MD=-0.7 km/h (-4.1%); ES=0.32; r=0.55	3
Foster et al. (2022)	22	Male	35.2 ± 8.6	Recreational runners	CPET on treadmill (1% incline; protocol: 3 to 4 speeds for 6 min until last submaximal speed, then 1% elevation increase per minute; MAS_{ex}: extrapolation of $\dot{V}O_2max$, ($\dot{V}O_2max$ + 27.53)/28.07); 1.61-km TT ($V_{1.61km}$: average velocity; 3.22-km TT ($V_{3.22km}$: average velocity)	Criterion validity	*Validity*: MAS_{ex} and $V_{1.61km}$: MD=0.97 km/h (+5.6%); ES=0.51; r=0.84 MAS_{ex} and $V_{3.22km}$: MD=-0.50 km/h (-3.0%); ES=0.27; r=0.86	3

Lacour et al. (1991)	24 8	Male Female	23.2 ± 4.6	Experienced runners (800 m – Marathon)	CPET on treadmill (protocol: 10.3-1.54-4 with 1 min breaks; MAS_{calc}: ($\dot{V}O_2max$-0.083)/energy cost of running); UMTT (protocol: 6-0.25-0.5; V_{UMTT}: velocity during last completed stage); 1500-m TT (V_{1500m}: average velocity)	Criterion validity	*Validity*: MAS_{calc} and V_{UMTT}: MD=0.25 km/h (+1.2%); ES=0.17; r=0.92 MAS_{calc} and V_{1500m}: MD=1.15km/h (+5.3%); ES=0.73; r=0.90 V_{UMTT} and V_{1500m}: MD=0.90km/h (+4.1%); ES=0.59; r=0.91	3
Lopes et al. (2015)	18	Male	28 ± 8	Long distance runners of different levels	CPET on treadmill (protocol 8-1-2; $MAS_{\dot{V}O_2max}$: lowest speed at which $\dot{V}O_2max$ was reached); UMTT (protocol: 8-1-2; V_{UMTT1}: velocity of the last completed stage; V_{UMTT2}: maximal velocity)	Criterion validity	*Validity*: $MAS_{\dot{V}O_2max}$ and V_{UMTT1}: MD=-0.7 km/h (-3.9%); ES=0.34; ICC=0.84 $MAS_{\dot{V}O_2max}$ and V_{UMTT2}: MD=-0.4 km/h (-2.2%); ES=0.19; ICC=0.85	3
Lorenzen et al. (2009)	23	Male	22.7 ± 3.4	Australian Rules Football players	CPET on treadmill (1% incline; protocol: 4 km/h below V_{3200m}-0.5-1; $MAS_{\dot{V}O_2max}$: lowest speed at which $\dot{V}O_2max$ was reached) 1500-m TT (V_{1500m}: average velocity); 3200-m TT (V_{3200m}: average velocity)	Criterion validity	*Validity*: $MAS_{\dot{V}O_2max}$ and V_{1500m}: MD=1.30 km/h (+8.0%); ES=1.75; r=-0.79 $MAS_{\dot{V}O_2max}$ and V_{3200m}: MD=-0.61 km/h (-3.7%); ES=0.83; r=-0.79	3
Lundquist et al. (2021)	33	Female	21.3 ± 1.6	Elite Australian Rules Football players	UMTT (protocol: 8-1-2; V_{UMTT}: maximal velocity); 1.2-km TT ($V_{1.2km}$: average velocity); 1.4-km TT ($V_{1.4km}$: average velocity); 1.6-km TT ($V_{1.6km}$: average velocity); 1.8-km TT ($V_{1.8km}$: average velocity); 2.0-km TT ($V_{2.0km}$: average velocity); 2.2-km TT ($V_{2.2km}$: average velocity)	Convergent validity	*Validity*: V_{UMTT} and $V_{1.2km}$: MD=0.6 km/h (+4.6%); ES=1.09; r=-0.66 V_{UMTT} and $V_{1.4km}$: MD=-0.1 km/h (-0.9%); ES=0.14; r=-0.96 V_{UMTT} and $V_{1.6km}$: MD=-0.9 km/h (-6.6%); ES=0.65; r=-0.85 V_{UMTT} and $V_{1.8km}$: MD=-0.6 km/h (-4,7%); ES=0.83; r=-0.91 V_{UMTT} and $V_{2.0km}$: MD=-0.6 km/h (-4.9%); ES=0.78; r=-0.94 V_{UMTT} and $V_{2.2km}$: MD=-1.0 km/h (-7.6%); ES=0.78; r=-0.95	3

Pallarés et al. (2019)	22	Male	25.7 ± 7.9	Trained runners and triathletes	CPET on treadmill (1% incline; protocol: 13 km/h less than Vmax during another test-1-1; $MAS_{\dot{V}O_2max}$: lowest speed at which $\dot{V}O_2$max was reached); UMTT (8-1-2; V_{UMTT}: last completed stage); track-individualized short ramp graded test (protocol: 13 km/h less than V_{max} from CPET-1-1; $V_{tracktest}$: V_{max}*0.8348 + 2.308 (97))	Criterion validity	*Validity*: $MAS_{\dot{V}O_2max}$ and V_{UMTT}: MD=-0.5 km/h (-2.6%); ES=0.42; ICC=0.92 $MAS_{\dot{V}O_2max}$ and $V_{tracktest}$: MD=0.0 km/h (+0.3%); ES=0.00; ICC=0.94	3
Paradisis et al. (2014)	25 23	Male Female	21.2 ± 1.9	Physical education students	CPET on treadmill (1%; protocol: 7 – 12-1-3; $MAS_{\dot{V}O_2max}$: lowest speed at which $\dot{V}O_2$max was reached); 20-m ST (20-m shuttles; protocol: 8.5-0.5-1; $V_{20mSTCALC}$: 0.0937*number of shuttles + 6.890)	Criterion validity	*Validity*: $MAS_{\dot{V}O_2max}$ and $V_{20mSTCALC}$: MD=-0.01 km/h (-0.1%); ES=0.00; r=0.93	3
Riboli et al. (2017)	17	Male	22.6 ± 1.8	Active and healthy adults	CPET on treadmill with a square-wave incremental protocol (1% incline; 5 workloads of 4 min each with at least 5 min rest in between; MAS_{ex}: extrapolated from VO_2 at submaximal velocities); incremental ramp test 1 (1% incline; 10-1-1; $MAS1_{30s}$: first speed where $\dot{V}O_2$max occurred and maintained for at least 30 s); incremental ramp test 2 (1% incline; 10-1-2; $MAS2_{30s}$: first speed where $\dot{V}O_2$max occurred and maintained for at least 30 s)	Criterion validity	*Validity*: MAS_{ex} and $MAS1_{30s}$: MD=3.9 km/h (+23.2%); ES=2.8; r=0.71 MAS_{ex} and $MAS2_{30s}$: MD=1.9 km/h (+10.7%); ES=1.7; r=0.80 $MAS1_{30s}$ and $MAS2_{30s}$: MD=-2.1 (-10.1%); ES=2.5; r=NA	3

Riboli et al. (2022)	16	Male	22.1 ± 1.8	Semi-professional soccer players	<u>CPET on a treadmill</u> with a continuous incremental protocol 1 (1%; 10-1-1; $MAS1_{30s}$: first speed where $\dot{V}O_2max$ occurred and maintained for at least 30 s); continuous incremental protocol 2 (1%; 10-1-2; $MAS2_{30s}$: first speed where $\dot{V}O_2max$ occurred and maintained for at least 30 s); discontinuous incremental protocol (1%; 5 workloads of 5 min each with at least 5 min rest in between; MAS_{ex}: extrapolated from VO_2 at submaximal velocities)	Criterion validity	*Validity*: $MAS1_{30s}$ and $MAS2_{30s}$ MD=-2.0 km/h (-10.3%); ES=1.29; r=0.75 $MAS1_{30s}$ and MAS_{ex}: MD=-3.4 km/h (-17.1%); ES=2.19; r=0.46 $MAS2_{30s}$ and MAS_{ex}: MD=-1.3 (-7.5%); ES=1.08; r=0.66	3
Sandford et al. (2019)	12 (4 4 4)	Male (National junior National senior International junior)	 18.5 ± 0.6 22.0 ± 1.8 17.3 ± 0.5	Middle-distance runners	CPET on treadmill (1% incline; 14 – 18-1-1; MAS_{30s}: first speed where $\dot{V}O_2max$ occurred and maintained for at least 30 s); 1500-m-TT (V_{1500m}: average pvelocity)	Criterion validity	*Validity*: MAS_{30s}: and V_{1500m}: MD=2.06 km/h (9.7%); ES=1.42; r=0.90	1

Sangan et al. (2021)	26 14 (11 for relia-bility part)	Male Female	38 ± 7 35 ± 3	Amateur runners	CPET on treadmill (protocol: 7 – 9-0.5-1; MAS_{30s}: first speed where $\dot{V}O_2max$ occurred and maintained for at least 30 s); one to three SRT_{RPE} on a running track (three 3-min stages with 1-min rest; intensity at RPE 10, 13, and 17; V_{RPE10}: average velocity during last min; V_{RPE13}: average velocity during last min; V_{RPE17}: average velocity during last min)	Criterion validity; Interday reliability	*Validity*: MAS_{30s}: and V_{RPE10}: MD=-4.43 km/h (-29.3%); ES=3.57; r=0.50 MAS_{30s}: and V_{RPE13}: MD=-2.66 km/h (-16.5%); ES=2.24; r=0.57 MAS_{30s}: and V_{RPE17}: MD=-0.27 km/h (-2.3%); ES=0.20; r=0.66 *Reliability:* V_{RPE10}: MD=-0.15 – 0.15 km/h (-1.4 – +1.4%); ES=0.14; CV=5.5%; ICC=0.76 V_{RPE13}: MD=0.02 – 0.20 km/h (+0.1 – 1.5%); ES=0.19 – 0.21; CV=4.5%; ICC=0.78 V_{RPE17}: MD=-0.32 – 0.04 km/h (-2.1 – +0.3%); ES=0.03 – 0.28; CV=3.9%; ICC=0.83	3 2
Schnitzler et al. (2010)	29 (17 in relia-bility part)	Male	19 ± 1.3	Physical education students	UMTT (protocol: 8-1-2; V_{UMTT}: velocity of last completed stage); two 3´30´´ ECT (protocol: 10 stages of 3 min with 0.5 min rest, first 5 stages at 75% V_{UMTT} and last 5 stages at freely chosen speed to cover maximal distance; V_{ECT}: average velocity of last 5 stages)	Conver-gent validity; Intraday reliability	*Validity*: V_{UMTT} and V_{ECT}: MD=-2.6 km/h (-16.5%); ES=1.27; r=0.76 *Reliability*: V_{ECT}: MD=-0.2 km/h (-1.6%); ES=0.11; CV=2.0%; ICC=0.98	3 2

Thron et al. (2022)	13	Male	23.4 ± 2.8	Trained soccer players	CPET on treadmill (1%; protocol: 6-2-3 with 0.5 min rest; $MAS_{Plateau}$: velocity at the onset of the plateau of VO2 (lower increase in VO_2 than 150 ml/min in at least the last minute of exercise); MAS_{30s}: first speed where $\dot{V}O_2max$ occurred and maintained for at least 30 s); UMTT (protocol: 10-1-2; V_{UMTT}: maximal velocity); 1500-m-TT (V_{1500m}: average velocity; V_{calc} - V_{1500m}*(0.766 + 0.117*1.5 km) (33))	Criterion validity	*Validity*: $MAS_{Plateau}$ and MAS_{30s}: MD=0.99 km/h (+6.3%); ES=1.61; r = 0.87; ICC=0.85 $MAS_{Plateau}$ and V_{UMTT}: MD=1.61 km/h (+19.3%); ES=2.03; r=0.79; ICC=0.69 $MAS_{Plateau}$ and V_{1500m}: MD=1.68 km/h (+10.7%); ES=1.77; r=0.65; ICC=0.51 $MAS_{Plateau}$ and V_{calc}: MD=0.67 km/h (+4.3%); ES=0.70; r=0.65; ICC=0.40 V_{UMTT} and V_{1500m}: MD=0.07 km/h (+0.4%); ES=0.14; r=0.74; ICC=0.72	1

The method claimed as the reference method in validity studies is underlined. Criterion validity refers to the comparison with an accepted gold standard method (i.e., CPET on a treadmill for MAS and radar, laser, or motion capture for MSS); convergent validity refers to the comparison with any other method. MQ – Methodological Quality (3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate); CPET – Cardiopulmonary Exercise Testing; Protocol: starting velocity (km/h)-increment (km/h)-duration of stages (min); MAS – Maximal Aerobic Speed; $\dot{V}O_2max$ – Maximal Oxygen Consumption; MD – Mean Difference; ES – Effect Size/Cohen´s d; ICC – Intraclass Correlation Coefficient; CV – Coefficient of Variation; UMTT – Université de Montréal Track Test; TT – Time Trial; VAM-EVAL – Vitesse Aerobie Maximale Evaluation; $Test_{3L}$ – Three Level Intermittent Field Test; HRmax – Maximal Heart Rate; UNCa test– National University of Catamarca test; CAR test – Carminatti's Incremental Intermittent Shuttle-Run test; 30-15 IFT – 30-second-15-second Intermittent Fitness Test; YoYo-IRT 1 – YoYo Intermittent Recovery Test 1; 20-m ST – 20-Meter Shuttle Run Test; SRT_{RPE} – Self-paced Submaximal Run Test; 3´30´´ ECT – 3-min-30-second Endurance Capacity Test.

Table 5.4: Overview of study characteristics and results on the assessment of maximal sprinting speed.

Study	Population				Short description	Type	Results	MQ
	N	Sex	Age	Description				
Akyildiz et al. (2022)	32	Male	21.18 ± 3.16	Amateur soccer players	Eight times a team sport simulation circuit with a 40-m sprint with radar (Stalker ATS II, 50 Hz); GPS (Polar Team Pro; 10 Hz) at chest and back	Criterion validity; Intraday reliability	*Validity:* Radar and GPS chest: MD=0.03 km/h (+0.1%); ICC=0.43 Radar and GPS back: MD=0.31 km/h (+1.3%); ICC=0.49 *Reliability:* GPS chest: ICC=0.43; CV=9.77% GPS back: ICC=0.49; CV=9.10%	3 3
Barbero-Alvarez et al. (2010)	21	Male	20.2 ± 2.3	Physical education students	Seven 30-m sprints: custom-made infrared timing gates with a 15-m split time (Omron E3S-CR11); GPS at back (SPI Elite, GPSports: 1 Hz)	Convergent validity	*Validity:* Light sensor and GPS: r=-0.93	1
Beato et al. (2018)	20	Male	21.0 ± 2.0	Students	Two 20-m-sprints with Radar (Stalker ATS II; 34.7 Hz); GPS at back (Viper; STATSports; 10 Hz)	Criterion validity; Interday reliability	*Validity:* Radar and GPS: MD=0.27 km/h (+0.7%); ES=0.07; r=0.98 *Reliability:* GPS: MD=0.24 km/h; ES=0.09; CV=0.7 %	3 1
Beato et al. (2019)	10	Male	22.0 ± 1.0	Team sports players	30-m sprint with 5-m split times and GPS: GPS at back (Apex; STATSports; 10 Hz); GPS at back (Viper; STATSports; 10 Hz)	Convergent validity; Intraday reliability	*Validity:* Apex and Viper: MD=0 km/h (0%); ES=0.00; ICC=0.96 *Reliability:* Apex: MD=-0.07 km/h (-0.3%); ES=0.03; ICC=0.97; CV=2.64 % Viper: MD=0.04 km/h (+0.1%); ES=0.02; ICC=0.91; CV=2.62 % On average, MSS was reached at the 20 – 30-m interval	3 1

Chahal et al. (2022)	4 9	Male Female	21.6 ± 1.6	Healthy active adults	One 45.72-m sprint with two smartphone video cameras (Kinovea; 60 Hz); 8 GPS units at back (Catapult S5 OptimEye; 10 Hz)	Convergent validity; Intraday reliability	*Validity:* Video and GPS: MD=-3.31 – 2.23 km/h (-11.8 – 8.0%); ES=0.03 – 0.78 *Reliability:* GPS: MD=5.54 km/h (+22.4%); ES=0.76; ICC=0.32; CV=7.01 %	0 3
Clark et al. (2019)	260	Male	NA	Professional football players	36.6-m sprints with split times at 9.1 and 18.3 m collected via online sources (<u>MSS modelled via a mono-exponential equation)</u>	Convergent validity	*Validity:* 0-9.1 m and modelled MSS: MD=13.07 km/h (+40.0%); r=0.85 9.1-18.3 m and modelled MSS: MD=3.70 km/h (+11.3%); r=0.69 18.3-36.6 m and modelled MSS: MD=-0.09 km/h (-0.3%); r=0.97	1
Coutts and Duffield (2010)	2	Male	32 ± 2	Moderately trained adults	Eight times a 128.5-m running circuit with a 20-m sprint and GPS: 6 GPS (2 SPI-10; 2 SPI Elite; 2 WiSPI; GPSports; 1 Hz)	Convergent validity; Intraday reliability	*Validity:* SPI-10 and SPI Elite: MD=0.60 km/h (+2.8%), ES=0.32; r=0.40 – 0.53 SPI-10 and WiSPI: MD=0.40 km/h (+1.9%); ES=0.21; r=0.40 – 0.53 WiSPI and SPI Elite: MD=0.20 km/h (+0.9%); ES=0.11; r=0.40 – 0.53 *Reliability:* SPI-10: CV=5.8 % SPI Elite: CV=2.3 % WiSPI: CV=4.9 %	0 0
Djaoui et al. (2017)	48	Male	22.6 ± 2.75	Professional and higher amateur soccer players	<u>Three 40-m sprints with GPS (GPSports SPI Elite; 15 Hz)</u>; 6 official matches (GPSports SPI Elite; 15 Hz); 14 Small-sided games of 90 min (GPSports SPI Elite; 15 Hz)	Convergent validity	*Validity:* 40-m sprint and matches: MD=-2.35 km/h (-7.5%); ES=1.07; r=0.52 40-m sprint and small-sided games: MD=-7.64 km/h (-24.4%); ES=3.17; r=NA Small-sided games and matches: MD=-5.29 km/h (-18.3%); ES=1.82; r=NA	0

Ferro et al. (2014)	**42**	**Male**	**21.14 ± 1.62**	**Physical Activity and Sports Sciences students**	**Three 30-m sprints with a laser sensor and with 10-m splits (LDM301; Jenoptik; 2000 Hz)**	**Criterion validity**	**Validity:** **Average velocities:** **20 – 30 and 0 – 10 m: MD=-10.04 km/h (-33.4%); ES=9.69** **20 – 30 and 10 – 20m: MD=-1.76 km/h (-5.1%); ES=1.44** **Maximum velocities:** **20 – 30 and 0 – 10 m: MD=-3.38 km/h (-11.4%); ES=3.88** **20 – 30 and 10 – 20 m: MD=-1.66 km/h (-5.2%); ES=1.30** **Most players reached MSS in 20-30-m split**	**0**
Fleureau et al. (2020)	5	Male	29.2 ± 4.1	Recreational handball players	Two 25-m sprints with a 12-camera Vicon motion capture system with one marker at the upper back (Vicon Nexus Z40; 250 Hz); 14 LPS antennas and one tag at the upper back (Kinexon; 20 Hz); carried out at the center and at the side of a handball field	Criterion validity	*Validity:* Center of court: Motion capture and LPS: MD=0.54 km/h (+2.9%); ES=0.50; r=1.00 Side of court: Motion capture and LPS: MD=0.61 km/h (+2.8%); ES=1.00; r=0.97	0

Fornasier-Santos et al. (2022)	13 5	Male Female	27.0 ± 6.7	Healthy, active adults	Three 40-m sprints with a linear motorized encoder (1080 Sprint; 333 Hz); Laser Speed device (MuscleLab; 1000 Hz); Radar (Stalker Pro II Sports Radar Gun; 46.875 Hz); GPS at the upper back (Vector S7; Catapult; 10 Hz); Timing gates at 0, 5, 10, 15, 20, 30, 40 m (Witty Microgate)	Convergent validity; Intraday reliability	*Validity:* Linear encoder and laser: MD=-0.11 km/h (-0.4%); ES=0.03 Linear encoder and radar: MD=-0.07 km/h (-0.2%); ES=0.02 Linear encoder and GPS: MD=0.00 km/h (0%); ES=0.00 Linear encoder and timing gates: MD=0.07 km/h (+0.2%); ES=0.02 Laser and radar: MD=0.04 km/h (+0.1%); ES=0.02 Laser and GPS: MD=0.11 km/h (+0.4%); ES=0.03 Laser and timing gates: MD=0.18 km/h (+0.6%); ES=0.04 Radar and GPS: MD=0.07 km/h (+0.3%); ES=0.02 Radar and timing gates: MD=0.14 km/h (+0.6%); ES=0.04 GPS and timing gates: MD=0.07 (+0.2%); ES=0.02 *Reliability:* Linear encoder: MD=0.14 km/h (+0.5%); CV=1.13% Laser: MD=0.18 km/h (+0.6%); CV=1.11% Radar: MD=0.29 km/h (+1.0%); CV=1.37% GPS: MD=0.25 km/h (+0.9%); CV=1.47% Timing gates: MD=0.14 km/h (+0.5%); CV=1.31%	0 0

Ghigiarelli et al. (2022)	16 6	Female Male	20.1 ± 1.5	Division II university team sports athletes	Three 30-m sprints with a laser speed device (MuscleLab 6000 ML6LDU02; 2.5 Hz); Video analysis (MySprint app; Apple Inc.; 120 fps)	Criterion validity, Interday reliability; Intraday reliability	*Validity:* Laser and video: MD=1.12 km/h (+4.0%), ES=0.53; r=0.98; ICC=0.92 *Reliability:* Intraday: Laser: MD=0.04 – 0.07 km/h (+0.1 – 0.3%); ES=0.02 – 0.08; ICC>0.98; CV<1.2 % Intraday: Video: MD=NA; ES=NA; ICC>0.97; CV<1.6% Interday: Laser: MD=-0.18 km/h (-0.6%); ES=0.09; ICC=0.98; CV=1.1 %	3 3 3
Helland et al. (2019)	17	Female	23 ± 3	Elite handball players	Two 30-m sprints with timing gates (NA) at 5, 10, 15, 20, and 30 m and mono-exponential modelled MSS	Intraday reliability	*Reliability:* MSS: MD= -0.14 km /h; CV=1.4%; r=0.99	1
Highton et al. (2012)	12	Male	22.3 ± 3.6	Amateur team sport players	<u>Three 30-m sprints with timing gates and 10-m splits (Speedtrap II, Brower Timing Systems</u>); two times three 30-m sprints on a NMT with a strain gauge (Woodway, Force 3.0; 100 Hz) on two different days	Convergent validity; Interday reliability, Intraday reliability	*Validity:* 0 – 10 m; overground: and NMT: MD=-6.20 km/h (-40.6%); ES=3.72; r=0.43 10 – 20 m; overground and NMT: MD=-7.70 km/h (-38.5%); ES=5.85; r=0.50 20 – 30 m; overground and NMT: MD=-10.33 km /h (-52.5%); ES=7.11; r=0.67 *Reliability:* Interday: NMT: MD=-0.07 km/h (-0.4%); ES=0.07; CV=1.8% Intraday: NMT: MD=-0.11 – 0.07 km/h (-0.5 – 0.4%); ES=0.08 – 0.10; CV=1.2% Most subjects reached MSS during the 20 – 30 m split during the overground running.	3 0 0

Hoppe et al. (2018)	6	Male	27 ± 2	Team sport players	Ten times a team sport simulation circuit with a 30-m sprint with timing gates at 5, 10, 20, and 30 m (Werthner Sport Consulting; TDS); GPS at back (Catapult: 10 Hz); GPS at back (Exelio srl; GPEXE PRO; 18 Hz); LPS at back with 12 antennas (Kinexon; 20 Hz); MSS was modelled mono-exponentially	Convergent validity, Intraday reliability	*Validity:* Timing gates and 10 Hz GPS: MD=0.0 km/h (0%); ES=0.00 Timing gates and 18 Hz GPS: MD=0.0 km/h (-0.2%); ES=0.00 Timing gates and 20 Hz LPS: MD=0.72 km/h (+2.1%); ES=2.00 *Reliability:* 10 Hz GPS: MD=-0.36 km/h (-1.2%); ES=1.0; CV=3.3% 18 Hz GPS: MD=0.0 km/h (0%); ES=0.0; CV=3.1% 20 Hz LPS: MD=0.36 km/h (+1.2%); ES=1.0; CV=1.6%	0 0
Johnston et al. (2014)	4	Male	29.0 ± 5.0	Well-trained adults	Ten 50-m- sprints with radar (Stalker ATS; 31.25 Hz); Two GPS units at the upper back (Catapult MinimaxX; Team Sport 2.5; 5 Hz)	Criterion validity; Intraday reliability	*Validity:* Radar and GPS 1: r=0.46 Radar and GPS 2: r=0.36 Reliability: GPS: ICC=0.01	0 3
Johnston et al. (2012)	8	Male	26.1 ± 4.1	Trained adults	Eight laps of a team sports simulation circuit with a 30-m sprint with timing gates and 10-m split times (Swift Performance); Two GPS units (Catapult MinimaxX S4; 10 Hz); Two GPS units (SPI-ProX; GPSports; 15 Hz)	Convergent validity; Intraday reliability	*Validity:* Timing gates and MinimaxX: MD=0.51 – 0.52 km/h (+2.3%); ES=0.22; r=0.89 – 0.91 Timing gates and GPSports: MD= -0.51 – 0.04 km/h; ES= 0.02 – 0.27 (-2.1 – 0.1%); r=0.64 – 0.76 MinimaxX and GPSports: MD=-0.19 km/h (-0.8%); ES=0.13 *Reliability:* Inter-unit: MinimaxX: MD=0.01 km/h (0%); ES=0.0; ICC=0.97 Inter-unit: GPSport: MD=-0.55 km/h (-2.3%); ES=0.3; ICC=-0.14	0 3

Lacome et al. (2019)	5	Male	25 ± 5	Elite rugby seven players	Five 40-m sprints with radar (Stalker ATS II; 48 Hz); GPS at the upper back (Sensoreverywhere V2; Digital simulation; 16 Hz)	Criterion validity	*Validity:* Radar and GPS: MD=-0.94 km/h (-3.0%); ES=0.78 Reliability: -	0
Massard et al. (2018)	23	Male	21.4 ± 3.8	Semi-professional football players	One 40-m sprint with dual-beamed timing gates and 10-m split times (TT Wireless SpeedLight); GPS at upper back (MinimaxX S4, Catapult 10 Hz) during sprint and matches in preseason and competitive season	Convergent validity	*Validity:* Timing gates and GPS during sprint: MD=-0.3 km/h (-1.0%); ES=0.21; r=0.84 Timing gates and GPS during matches: MD=0.8 km/h (+1.9%); ES=0.39; r=NA GPS during sprint and GPS during matches: MD=1.1 km/h (+3.0%); ES=0.66; r=NA	0
Morin and Sève (2011)	11	Male	24.4 ± 3.9	Physical education students	One 100-m sprint in the field with radar (Stalker ATS; 35 Hz); One 100-m sprint on a motorized instrumented treadmill with piezoelectric force transducers (ADAL3D-WR; Medical Development; 1000 Hz); MSS was modelled bi-exponentially	Criterion validity	*Validity:* Radar and treadmill: MD=-6.98 km/h (-21.9%); ES=4.27; r=0.89	1

Ogris et al. (2012)	6	Male	22 ± 4	Moderately trained soccer players	Six 26.5-m sprints with a motion capture system with 8 cameras (Vicon; 50 Hz); LPS with 12 antennas and the transponder worn on the back (lpm04.59; 45.45 Hz)	Criterion validity	*Validity:* Motion capture and LPS: MD=1.68 km/h (+6.78%)	0
Roe et al. (2017)	9	Male	19.0 ± 0.8	Professional rugby union player	Three 40-m sprints with radar (Stalker ATS II; 50 Hz); Timing gates with 10-m split times (Brower Timing Systems); Three GPS units on the back (Optimeye S5; Catapult; 10 Hz)	Criterion validity	*Validity:* Radar and GPS: MD=0.25 – 0.50 km/h (-0.77 - -1.35%); ES=0.13 – 0.25; r>0.95 Radar and timing gates: MD=-0.76 km/h (-2.39%); ES=0.37; r=0.97	0
Romero-Franco et al. (2017)	12	Male	21.4 ± 3.9	Trained sprinters	Six 40-m sprints with radar (Stalker ATS II; 46.88 Hz); Video analysis with split times at 5, 10, 15, 20, and 30 m (MySprint App, Apple Inc.)	Criterion validity; Intraday reliability	*Validity:* Radar and video: MD=0.25 km/h (+0.8%); ES=0.07; r=0.99; ICC=0.99 *Reliability:* Video: CV=0.14% Radar: CV=0.11%	1 0
Sagiroglu et al. (2021)	16	Male	27.22 ± 4.70	Amateur soccer players	Three 40-m sprints with radar (Stalker ATS II; 50 Hz); Two GPS-units on the chest (Polar Team Pro GPS; 10 Hz)	Criterion validity; Intraday reliability	*Validity:* Radar and GPS: MD=0.14 km/h (+1.6%); ES=0.02; r=0.94 *Reliability:* GPS: CV=5 – 6% Radar: CV=6%	3 0

Simpering-ham et al. (2019)	27 (9 for Inter-day reliabil-ity)	Male	18.6 ± 0.6	Amateur rugby union players	Three 30-m sprints with radar on four different days (Stalker ATS II; 47 Hz)	Intraday reliability; Interday reliability	*Reliability:* Intraday: CV=1.8%; ICC=0.95 Interday: CV=2.1 – 2.4%; ICC=0.83 – 0.93	3 3
Vescovi (2012)	140	Female	23.9 ± 2.8	Profes-sional soccer players	Two 35-m sprint with timing gates and split times at 5, 10, and 20 m (Brower Timing Systems)	Convergent validity	*Validity:* 0 - 5 m and 5 - 10 m: MD=2.9 km/h (+19.2%); ES=2.89 5 - 10 m and 10 - 20: MD=3.2 km/h (+17.8%); ES=3.56 10 - 20 m and 20 - 35 m: MD=2.2 km/h (+10.4%); ES=2.44 Reliability: - Most players reached MSS in the 20 – 35 m interval.	0
Willmott et al. (2019)	14	Male	23 ± 3	Moder-ately-trained adults	Two 40-m sprints and a team sports simulation circuit with a 20-m sprint and two different GPS devices (Field-Wiz; UNA Sports Medicine; 10 Hz; Catapult MinimaxX S4; Catapult Innova-tions; 10 Hz)	Convergent validity; Intraday reliability	*Validity:* 40-m sprint: FieldWiz and MinimaxX: MD=-0.3 - 0.1 km/h (-1.2 - +0.4%); ES= 0.05 – 0.23; ICC>0.8 40-m sprint vs. 20-m sprint during circuit: MinimaxX: MD=-3.0 km/h (-10.8%); ES=2.04; ICC>0.8 FieldWiz: MD=-2.6 km/h (-9.3%); ES=1.41; ICC>0.8 Reliability: FieldWiZ: MD=0.1 km/h (+0.4%); ES=0.05; CV=0.9 – 2.3%; ICC>0.9	1 3

Young et al. (2008)	35 (A) 30 (B)	Male	NA	Professional Australian Rules Football players	Club A: 40-m sprint with split times at 10 and 20 m and timing gates (Swift Timing); Club B: 30-m sprint with split times at 10 and 20 m and timing gates (KMS; Fitness Technologies)	Convergent validity	*Validity:* Club A: 0-10 m and 10-20 m: MD=9.95 km/h (+52.4%); r= 0.94 10-20 m and 20-40 m: MD=2.55 km/h (+8.8%); r=0.67 Club B: 0-10 m and 10-20 m: MD=7.85 km/h (+37.0%); r=0.94 10-20 m and 20-30 m: MD=2.00 km/h (+6.7%); r=0.77	3
Zabaloy et al. (2021)	19	Male	22.5 ± 5.3	Amateur rugby players	<u>Two 30-m sprints with radar (Stalker ATS II; 47 Hz);</u> timing gates with split times at 5, 10, 20, and 25 m (Witty System; Microgate)	Criterion validity; Intraday reliability	*Validity:* Radar and best 5-m-split: MD=0.13 km/h (+0.5%); ES=0.07; r=0.93; ICC=0.96 Radar and best 10-m-split: MD=-0.30 km/h (-1.0%); ES= 0.14; r=0.97; ICC=0.98 *Reliability:* Radar: MD=-0.11 km/h (-0.4%); CV=1.14%; ICC=0.99 Best 10-m-split: MD=-0.04 km/h (-0.1%); CV=1.47%; ICC=0.98 Best 5-m-split: MD=-0.11 km/h (-0.4%); CV=1.70%; ICC=0.97 No significant difference in the 20-25 and 25-30-m-splits, indicating that subjects reached MSS between 20 and 30 m.	3 3

Zabaloy et al. (2021)	49	Male	24.16 ± 4.08	Amateur rugby players	Two 50-m sprints with timing gates and split times at 10, 20, 30, and 40 m (Witty System, Microgate)	Validity; Intraday reliability:	*Validity:* 10-20 m and 20-30 m: MD=1.04–2.09 km/h (0 - +35%); ES=0.62-0.98 20-30 m and 30-40 m: MD=-0.25-0.22 km/h (0 - +31.1%); ES=0.07-0.08 30-40 m and 40-50 m: MD=-0.24--0.65 km/h (0-32.9%); ES=0.11-0.26 *Reliability:* 10-m-split: CV=2.43%; ICC=0.95 20-m-split: CV=2.19%; ICC=0.97 30-m-split: CV=1.93%; ICC=0.98 40-m-split: CV=1.90%; ICC=0.98 50-m-split: CV=2.26%; ICC=0.98 50 - 58.6% of the players reached their MSS between 20 and 30 m or between 30 and 40 m.	0 2

The method claimed as the reference method in validity studies is underlined. Criterion validity refers to the comparison with an accepted gold standard method (i.e., CPET on a treadmill for MAS and radar, laser, or motion capture for MSS); convergent validity refers to the comparison with any other method. MQ – Methodological quality (3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate); MD – Mean difference; ES – Effect size/Cohen´s d; ICC – Intraclass Correlation Coefficient; CV – Coefficient of variation; GPS – Global Positioning System; Hz – Hertz; MSS – Maximal Sprinting Speed; LPS – Local Positioning System; NA – Not Available; NMT – Non-Motorized Treadmill

Table 5.5: Descriptive overview.

	Participants [number (mean ± SD; range)]	**Age [mean ± SD (range)]**	**Distribution of sexes [number of studies]**	**Backgrounds [number of studies]**
MAS	685 (21.4 ± 8.8; 8–48)	24.5 ± 5.8 years (18.3–41.2 years)	Men: n=22 Women: n=3 Both: n=3	Soccer/football/futsal players: n=10 Sports students: n=5 Runners: n=9 Healthy active people: n=4
MSS	936 (27.5 ± 47.9; 2–260)	23.5 ± 3.3 years (18.6–31.0 years)	Men: n=25 Women: n=2 Both: n=3	Soccer/ football/rugby/ handball: n=19 Healthy active people: n=6 Sports students: n=4 Runners: n=1

MAS – Maximal Aerobic Speed; MSS – Maximal Sprinting Speed; SD – Standard Deviation.

Assessment of methodological quality

The validity of methods to assess MAS was reported in 28 studies using 69 different methods. For 23 studies the methodological quality for validity was rated *very good* (Bellenger et al., 2015; Benhammou et al., 2021; Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Billat et al., 1996; Cappa et al., 2014; Carminatti et al., 2013; Čović et al., 2016; Da Silva & Machado, 2015; Darendeli et al., 2021; Dillon et al., 2021; Dittrich et al., 2011; Foster et al., 2022; Lacour et al., 1991; Lopes et al., 2015; Lorenzen et al., 2009; Lundquist et al., 2021; Pallarés et al., 2019; Paradisis et al., 2014; Riboli et al., 2017; Riboli et al., 2022; Sangan et al., 2021; Schnitzler et al., 2010) and for five studies *doubtful* (Barbero-Alvarez et al., 2015; Bernard et al., 2000; Berthoin et al., 1996; Sandford, Rogers, et al., 2019; Thron, Woll, et al., 2022). Intraday (one method) and interday reliability (six methods) of MAS was reported in one and four studies, respectively. The methodological quality of the study reporting intraday reliability was rated *adequate* (Schnitzler et al., 2010). For interday reliability, two studies were rated *very good* (Benhammou et al., 2021; Čović et al., 2016), one was *adequate* (Sangan et al., 2021) and one was *doubtful* (Cappa et al., 2014).

Regarding MSS, validity was reported in 28 studies using 53 different methods. Methodological quality was rated as *very good* (n=8) (Akyildiz et al., 2022; Beato & de Keijzer, 2019; Beato et al., 2018; Ghigiarelli et al., 2022; Highton et al., 2012; Sagiroglu et al., 2021; Young et al., 2008; Zabaloy, Freitas, et al., 2021), *doubtful* (n=5) (Barbero-Álvarez et al., 2010; Clark et al., 2019; Morin & Sève, 2011; Romero-Franco et al., 2017; Willmott et al., 2019), and as *inadequate* (n=15) (Chahal et al., 2022; Coutts & Duffield, 2010; Djaoui et al., 2017; Ferro et al., 2014; Fleureau et al., 2020; Fornasier-Santos et al., 2022; Hoppe et al., 2018; Johnston et al., 2014; Johnston et al., 2012; Lacome et al., 2019;

Massard et al., 2018; Ogris et al., 2012; Roe et al., 2017; Vescovi, 2012; Zabaloy, Giráldez, et al., 2021). Intraday and interday reliability was assessed in 17 and four studies (for 32 and four methods, respectively). Studies reporting intraday reliability achieved a rating for methodological quality of *very good* (n=8) (Akyildiz et al., 2022; Chahal et al., 2022; Ghigiarelli et al., 2022; Johnston et al., 2014; Johnston et al., 2012; Simperingham et al., 2019; Willmott et al., 2019; Zabaloy, Freitas, et al., 2021), *adequate* (n=1) (Zabaloy, Giráldez, et al., 2021), *doubtful* (n=2) (Beato et al., 2018; Helland et al., 2019), and *inadequate* (n=6) (Coutts & Duffield, 2010; Fornasier-Santos et al., 2022; Highton et al., 2012; Hoppe et al., 2018; Romero-Franco et al., 2017; Sagiroglu et al., 2021). Regarding interday reliability, studies were rated as *very good* (n=2) (Ghigiarelli et al., 2022; Simperingham et al., 2019), *doubtful* (n=1) (Beato & de Keijzer, 2019), and *inadequate* (n=1) (Highton et al., 2012). More detailed information about the methodological quality of the studies can be found in Appendix 3 Paper III Supplementary Table 2.

Main findings for criterion validity and reliability

Maximal aerobic speed: Reference methods used for validity testing. As a reference method for validity testing, MAS was assessed by CPET on a treadmill in 21 studies (criterion validity), by incremental continuous field tests (UMTT or Vitesse Aerobie Maximale Evaluation (VAM-EVAL)) in six studies, and by the 30-15 Intermittent Fitness Test (30-15 IFT) in one study (convergent validity).

Cardiopulmonary exercise testing. Different protocols for CPET were compared with each other seven times. In terms of validity, the results differed between 0.1 and 3.9 km/h (ES=0.11 – 2.8; r/ICC=0.46 – 0.80). Intraday or interday reliability was not reported for different treadmill protocols. Different definitions of MAS were compared 12 times with deviations of 0 – 0.99 km/h (ES=0 – 1.61; r/ICC=0.85 – 1.0). Interday reliability of definitions for MAS was reported one time with a mean difference of -0.1 km/h (ES=0.11; r/ICC=0.87), while intraday reliability was not reported.

Incremental field tests. Validity of incremental continuous field tests (UMTT, VAM-EVAL, track-individualized short ramp graded test, or National University of Catamarca test) to estimate MAS were tested 12 times against CPET on a treadmill as the reference method. The mean difference between the estimated MAS and the MAS retrieved by CPET ranged from -2.0 – 1.61 km/h (ES=0 – 2.03; r/ICC=0.83 – 0.96). Intraday or interday reliability was not reported for incremental continuous field tests.

Time trials. Validity for time trials (1500 m, 3200 m, or 5 min) to estimate MAS was examined nine times. The mean difference from the gold standard, i.e., CPET, ranged from 0.1 – 2.06 km/h (ES=0.08 – 1.75; r/ICC=0.51 – 0.94). There was no study investigating interday or intraday reliability of time trials.

Shuttle runs. Results from different shuttle runs (futsal specific shuttle test, 30-15 IFT, Carminatti's shuttle test, 20-m shuttle test) to estimate MAS were compared to CPET four times for validity testing. The mean differences ranged from -0.7 – 4.0 km/h (ES=0 – 2.04) with a correlation between 0.55 and 0.93. Regarding interday reliability, one study reported results for the 30-15 IFT with a mean difference of 0.3 km/h (ES=0.29; ICC=0.91; CV=1.8%). Intraday reliability from one study for the 3-min 30-second Endurance Capacity Test showed a mean difference of -0.2 km/h (ES=0.11; ICC=0.98; CV=2.0%).

Other/individualized methods. In two studies, validity of other fitness tests to estimate MAS were investigated. The comparison of the self-paced submaximal running test in which the velocities of the stages were self-chosen according to ratings of perceived exertion (RPE) 10, 13, and 17 with CPET showed mean differences between -0.27 and -4.43 km/h (ES=0.20 – 3.57; r/ICC=0.50 – 0.66). Interday reliability was reported for each test (n=2). Results for the mean differences were -0.32 – 0.20 km/h (ES=0.03 – 0.28; r/ICC=0.76 – 0.99; CV=3.9 – 16.9%). Intraday reliability was not examined.

Maximal sprinting speed: Reference methods used for validity testing. As a gold standard method to assess MSS, 20 – 100-m linear sprints with radar or laser measurement were used in 11 studies investigating validity. 30 – 40-m sprints with 5- or 10-m split times and timing gates were used in eight studies, a 40-m sprint with GPS measurement was used in four studies, 25 – 26.5-m sprints with a motion capture system were used in two studies, a 45.72-m sprint with video analysis via a smartphone app was used in one study, and a 40-m sprint with a linear encoder was also used in one study as a reference method to assess MSS. In one study, data were collected via online-sources and the reference MSS was modelled mono-exponentially based on the data.

Radar/Laser technology. In one study validity of radar and laser measurement was tested with a linear encoder as the reference method. The results differed between -0.11 and -0.07 km/h (ES=0.02 – 0.03). Intraday reliability was reported four times and ranged from 0.04 – 0.29 km/h (ES=0.02 – 0.08; ICC>0.95; CV<1.8%). Interday reliability was reported two times for radar/laser measurement with a mean difference of -0.18 km/h (ES=0.09; ICC=0.83 – 0.98; CV<2.4%).

Timing gates. In two studies validity for the assessment of MSS with timing gates was examined with radar as the reference method. The results differed between -0.13 and -0.76 km/h (ES=0.07 – 0.37; r/ICC=0.93 – 0.98). In four studies, 5- or 10-m split times during 30 – 50-m sprints were compared with each other, resulting in differences between -0.06 and 9.95 km/h (ES=0.07 – 3.56; r/ICC=0.67 – 0.94). Intraday reliability for measurements of MSS with timing gates was reported five times. Results ranged from -0.14 – 0.14 km/h (r/ICC=0.95 – 0.99; CV=1.14 – 2.43%). Interday reliability was not reported.

Global and local positioning systems. Validity of GPS or LPS to assess MSS was examined eight times with radar measurement. The results differed by values between 0.03 and 0.94 km/h (ES=0.02 – 0.78; r/ICC=0.36 – 0.98). GPS/LPS was compared four times with video analysis or motion capture systems. The results differed between -3.31 and 2.23 km/h (ES=0.03 – 1.00; r/ICC=0.97 – 1.00). Intraday reliability of GPS/LPS measurements to assess MSS during linear sprinting was examined 12 times with results differing between -0.36 and 5.54 km/h (ES=0 – 1.0; r/ICC=0.14 – 0.97; CV=0.7 – 9.77%). Interday reliability was examined one time with a mean difference of 0.24 km/h (ES=0.09; CV=0.7%).

Video analysis via smartphone applications. Validity of video analysis with a smartphone app was examined two times with radar/laser measurement. The results differed between 0.25 and 1.12 km/h (ES=0.07 – 0.53; r/ICC=0.92 – 0.99). Intraday reliability was determined two times with an ICC>0.97 and CV<1.6%. Interday reliability was not examined.

Treadmill sprinting. Validity of a sprint on a motorized treadmill with piezoelectric force transducers with radar as the reference on a running track was determined one time. The results showed a mean difference of -6.98 km/h (ES=4.27; r=0.89). Interday and intraday reliability for the non-motorized treadmill was examined one time each with an CV of 1.8 and 1.2%, respectively.

5.2.5 Discussion

Overview

The aim was to systematically review the scientific literature regarding the validity and reliability of different methods to assess ASR, i.e., methods to assess MAS and MSS. The high number of studies and methods included in this review emphasizes the popularity of both MAS and MSS in research and practice. As a combination of MAS and MSS, ASR has the advantage of normalizing absolute values for individualizing high-intensity training above MAS to take individual tolerances to high-intensity efforts into account (Blondel et al., 2001; Sandford et al., 2021).

Regarding MAS, CPET on a treadmill is mostly used as a gold standard method (21 out of 28 studies; criterion validity), but with different protocols or definitions of MAS. The most studied methods could be assigned to CPET (n=19) and time trials (n=20), followed by incremental continuous field tests such as the UMTT (n=12). The least studied methods were shuttle runs (n=10). Intraday (n=1) and interday reliability (n=2) of methods to assess MAS were investigated equally but overall very rarely.

With respect to MSS, radar measurements (11 out of 28 studies; criterion validity) and distances between 20 and 40 m (23 out of 28 studies) are mostly used as gold standard methods for validity testing. Validity was assessed for GPS/LPS measurements most times (n=18), followed by timing gates including different split distances (n=8), and video analysis (n=2). Radar and laser were (n=2) validated against a linear motorized encoder. Intraday reliability (n=22) was investigated remarkedly more frequently than interday reliability (n=2).

Maximal aerobic speed

Cardiopulmonary exercise testing: Although CPET on a treadmill is considered as the gold standard method to assess MAS, the testing protocols or definitions, i.e., the methods on how to retrieve MAS based on CPET, are yet to be clarified. The most used protocols are (square-wave) incremental protocols with and without resting in between the stages with different starting velocities, increments or duration of stages, or protocols based on individual performance, e.g., starting speed related to theoretical maximal heart rate (Barbero-Alvarez et al., 2015; Bernard et al., 2000; Berthoin et al., 1996; Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Billat et al., 1996; Cappa et al., 2014; Čović et al., 2016; Da Silva & Machado, 2015; Dittrich et al., 2011; Foster et al., 2022; Lacour et al., 1991; Lopes et al., 2015; Lorenzen et al., 2009; Pallarés et al., 2019; Paradisis et al., 2014; Riboli et al., 2017; Riboli et al., 2022; Sandford, Rogers, et al., 2019; Sangan et al., 2021; Thron, Woll, et al., 2022). The definitions of MAS used in the studies were also different, e.g., the first speed when $\dot{V}O_2max$ occurred with no further specification (Billat et al., 1996; Cappa et al., 2014; Da Silva & Machado, 2015; Lopes et al., 2015; Lorenzen et al., 2009; Pallarés et al., 2019; Paradisis et al., 2014) ~~or~~, calculated based on VO_2 kinetics (Barbero-Alvarez et al., 2015; Bernard et al., 2000; Berthoin et al., 1996; Foster et al., 2022; Lacour et al., 1991; Riboli et al., 2017; Riboli et al., 2022) the first speed of the 30-s interval of $\dot{V}O_2max$ (Riboli et al., 2017; Riboli et al., 2022; Sandford, Rogers, et al., 2019; Sangan et al., 2021), the speed at the onset of the plateau of VO_2 (Dittrich et al., 2011; Thron, Woll, et al., 2022), or the final speed reached during CPET (Berthoin et al., 1996; Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Čović et al., 2016). Regarding validity of CPET on a treadmill to determine MAS, different incremental continuous protocols yielded similar results when the increments and stage durations were multiples of each other (e.g. 1 km/h increment and 2 min duration of stages versus 0.5 km/h increment and 1 min duration of stages) (Billat et al., 1996). For the same increments, longer durations of stages lead to lower results of MAS (-2.1±0.5 – -2.0±1.45 km/h) (Riboli et al., 2017; Riboli et al., 2022). MAS shows significantly higher values when using square wave protocols (with resting periods) than when examined by incremental continuous protocols (Riboli et al., 2017; Riboli et al., 2022). Because different protocols used in the CPET yield different results in MAS, no conclusion can be drawn in consideration of the included studies. However, taken the definition of MAS into account, i.e., the first speed associated with $\dot{V}O_2max$, it is crucial for the subjects to actually reach $\dot{V}O_2max$ during the treadmill test. That can be verified by the incidence of a VO_2 plateau or other criteria measures such as blood lactate, respiratory exchange ratio, heart rate, or the rating of perceived exertion (Midgley, McNaughton, Polman, et al., 2007). Regarding the protocol, continuous incremental exercises with durations between 8 and 16 min (e.g., starting at 4 or 6 km/h for recreational subjects and at 8 or 10 km/h for trained subjects with 1 km/h increments every minute) are suggested to reach $\dot{V}O_2max$ and might therefore also be suitable for assessing MAS (Midgley, McNaughton, Polman, et al., 2007; Niemeyer et al., 2021). When MAS was determined at the onset of the plateau of $\dot{V}O_2max$, i.e., VO_2 reaching a steady-state during an incremental treadmill test, the results differed remarkedly from MAS determined at the 30-s interval of $\dot{V}O_2max$ (Thron, Woll, et al., 2022). These discrepancies might be explained by the definition of a leveling-off of VO_2 lasting at least 1 min (Meyer & Kindermann, 1999) and the 30-s interval of $\dot{V}O_2max$ almost always occurs at the end of an incremental exercise close to the maximal speed (Buchheit, 2010; Thron, Woll, et al., 2022). Further results regarding comparisons of definitions of MAS indicate that the final speed reached during incremental exercise as well as velocities based on calculations or extrapolations of VO_2 to assess MAS are associated with a higher input of anaerobic resources than the first speed at the steady-state of VO_2, i.e. the speed at the onset of the plateau of $\dot{V}O_2max$ and therefore the first speed associated with $\dot{V}O_2max$ when mainly aerobic resources are used (Berthoin et al., 1996; Da Silva & Machado, 2015). Such considerations should be taken into account when assessing MAS with CPET to determine the first speed associated with $\dot{V}O_2max$ at which energy production is still largely aerobic (Buchheit, 2010; Thron, Woll, et al., 2022). Especially for the purpose of HIIT prescription based on MAS or ASR, using definitions as the speed of the 30-s interval of $\dot{V}O_2max$ or the final velocity reached during CPET could lead to different adaptations as intended or even overtraining.

The one study addressing interday reliability for MAS determined by CPET reported good relative reliability. However, since different protocols on the treadmill and different definitions of MAS are currently used and partly differ regarding their results, further studies should address validity and especially reliability of a consistent definition of MAS.

Incremental continuous field tests: Léger and Boucher (1980) developed and validated an incremental continuous field test to indirectly determine $\dot{V}O_2max$ – the UMTT. Further, the UMTT and variations of it (e.g., VAM-EVAL) were then used to estimate MAS as they are less time and material consuming and need less expertise to implement than CPET (Buchheit, Simpson, et al., 2012; Lacour et al., 1991). Regarding the validity of these field tests, the results depend on the protocols and definitions used in the reference measure and in the field test. In all of the studies (n=8) investigating the validity of incremental continuous field tests to estimate MAS, CPET was used as the reference measure (criterion validity). When the identical protocols were implemented in the CPET and the field tests, two studies reported good validity (Lopes et al., 2015; Pallarés et al., 2019). However, one study reported significant differences (Cappa et al., 2014). Lopes et al. (2015) and Pallarés et al. (2019) validated the UMTT, whereas Cappa et al. (2014) developed a new field test (i.e., University of Catamarca test) and validated it with CPET on a treadmill with the same protocol. The University of Catamarca test consisted of a hexagon with 20-m long sides so that the participants ran around corners and not as in the UMTT on a linear and curved track potentially leading to an earlier exhaustion in the Catamarca test (Cappa et al., 2014). Comparisons of the final speed reached in the UMTT with the MAS calculated according to Lacour et al. (1991) showed good validity (Berthoin et al., 1996; Lacour et al., 1991), whereby heterogenous results were found when the maximal speed during CPET (Berthoin et al., 1996; Berthon, Fellmann, et al., 1997), or the speed associated with $\dot{V}O_2max$ (Billat et al., 1996; Lopes et al., 2015; Pallarés et al., 2019)were used as the definitions of MAS during CPET. The final velocity reached during UMTT resulted in higher values (+1.61 km/h) than the speed at the onset of the VO_2 plateau (Thron, Woll, et al., 2022). Therefore, using the final velocity of UMTT to estimate MAS and prescribe training, e.g. HIIT, might lead to higher intensities as intended what can be fatal in terms of maladaptation or even overtraining. Although no study on reliability could be included, Léger and Boucher (1980) reported good reliability of the maximal metabolic equivalents related to the UMTT.

Time trials: Set-distance time trials with different distances or 5-min time trials are often used in research and practice to estimate MAS because of an easy implementation even for larger groups (Bellenger et al., 2015; Sandford, Allen, et al., 2019). While the average speed during 5-min time trials achieved similar results as the final speed reached during CPET or the UMTT in men of different fitness or amateur soccer players (Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Darendeli et al., 2021), the results on the validity of set-distance time trials are heterogeneous. When 1500 or 1610-m time trials were compared to CPET (criterion validity), all of the studies reported an over-estimation of MAS investigating different participants, such as male and female runners, male Australian rules football players, or male trained soccer players, and with different definitions and protocols used in the CPET (Foster et al., 2022; Lacour et al., 1991; Lorenzen et al., 2009; Sandford, Rogers, et al., 2019; Thron, Woll, et al., 2022). Bellenger et al. (2015) and Lundquist et al. (2021) investigated set-distance time trials between 1200 and 2200 m with male and female Australian rules football players. However, they used the final speed reached in the UMTT as the reference measure (convergent validity). For female subjects, the smallest effect and largest relationship was examined between the 1400-m time trial and the UMTT (Lundquist et al., 2021), whereby for male subjects the smallest effect was found for the 2000-m time trial (Bellenger et al., 2015). These results indicate that the validity of set-distance time trials depends on which distance is used for which sex, type of sports, or fitness. For this reason, Bellenger et al. (2015) suggested to predict MAS from the running speed for any time trial distance between 1200 and 2200 m with the equation: MAS = average speed * (0.766 + 0.117 * distance). However, the validity of this equation could not be confirmed for a 1500-m time trial in trained male soccer players (Thron, Woll, et al., 2022). When the studies investigating criterion validity of time trials with an accepted gold standard, i.e. CPET, are considered (n=6), the results indicate that the time or distance should be selected according to the background of the subject (sex, type of sports, fitness). For lower fitness or subjects associated with sports based on higher speeds and mainly anaerobic energy supply, e.g. most team sport players or sprinters, shorter distances might be favorable (e.g., 1200 – 1400 m), whereas for (endurance) trained athletes longer distances (e.g., 1500 – 2000 m) could reflect an average speed more similar to MAS (Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Foster et al., 2022; Lacour et al., 1991; Lorenzen et al., 2009; Thron, Woll, et al., 2022)

Shuttle runs: Shuttle runs are defined by stages with increasing speed or distance and changes of direction, often by 180°. Most shuttle-runs include active or passive rest (Buchheit, 2010). While the peak speed of shuttle runs with passive rest (futsal specific shuttle run; 30-15 IFT) overestimated MAS assessed during CPET (Barbero-Alvarez et al., 2015; Čović et al., 2016), shuttle-runs with active or no rest (Carminatti's test, 20-m shuttle run) yielded more similar results to CPET (criterion validity) (Dittrich et al., 2011; Paradisis et al., 2014). The passive rest could have provided an opportunity to recover in-between the shuttles so that a higher final speed was reached (Buchheit, 2010; Čović et al., 2016). The results for the 30-15 IFT and the 3-min 30-s endurance capacity test, showed good interday and intraday reliability, respectively (Čović et al., 2016; Schnitzler et al., 2010). When only studies using an accepted gold standard to assess MAS, i.e. CPET (n=4; criterion validity), are considered, most of the studies (two out of three) determining final speed during a shuttle run could not confirm its validity (large overestimation by shuttle runs) (Barbero-Alvarez et al., 2015; Čović et al., 2016). These results might be mainly due to shuttle runs demanding more anaerobic resources and a higher energy cost of running because of change of direction movements (Buchheit, 2010). These results indicate that MAS cannot be examined by the final speed reached during a shuttle.

Other/Individualized tests: Sangan et al. (2021) validated a field test that is based on individual RPE during three stages (RPE 10, 13, and 17) lasting three minutes each. The comparisons of the average velocities during the last minutes of the three stages and MAS retrieved by CPET showed poor criterion validity, while absolute and relative intraday reliability can be rated as good. While validity for the three-level tests needs to be investigated further with CPET, validity of a field tests based on RPE cannot be confirmed (Benhammou et al., 2021; Sangan et al., 2021).

Maximal sprinting speed

Radar/Laser technology: As the MSS reflects the maximal overall possible sprinting speed a subject can reach, it marks the upper limit of the ASR by providing information about the maximal physiological, mechanical, and coordinative output during sprinting (Sandford et al., 2021). Measuring the speed profile during linear sprinting with laser or radar devices is considered as the gold standard method to examine MSS (Beato et al., 2018; Romero-Franco et al., 2017). One study examined and confirmed convergent validity of both radar and laser measurement during 40-m sprints to assess MSS with a linear motorized encoder as the reference measure (Fornasier-Santos et al., 2022). The validation of accepted gold standard methods becomes challenging in the absence of alternative gold standards. However, previous studies have demonstrated the accuracy of laser and radar devices in assessing various sprinting characteristics (Haugen & Buchheit, 2016). Both absolute and relative intraday reliability was reported good in all studies (n=4) (Fornasier-Santos et al., 2022; Ghigiarelli et al., 2022; Simperingham et al., 2019; Zabaloy, Freitas, et al., 2021) as well as absolute and relative interday reliability (n=2) (Ghigiarelli et al., 2022; Simperingham et al., 2019).

Timing gates: Timing gates are commonly used to assess sprinting characteristics as they conveniently provide sprinting times for distinct distances (Altmann et al., 2019; Zabaloy, Freitas, et al., 2021). When the average speed assessed during 5- and 10-m splits was compared to MSS measured with radar or a linear motorized encoder (Fornasier-Santos et al., 2022; Roe et al., 2017; Zabaloy, Freitas, et al., 2021), the results indicate that 10-m splits are also sufficient to assess MSS with timing gates compared to 5-m splits. Moreover, Zabaloy, Freitas, et al. (2021) did not detect significant differences in the 20 – 25 and 25 – 30-m splits indicating that participants reached MSS between 20 and 30 m. With respect to the total distances for the assessment of MSS, distances between 20 and 100 m are used in the included studies (Coutts & Duffield, 2010; Morin & Sève, 2011). Although no study compared different total distances, results of comparisons of the split times indicate, that distances between 20 and 40 m should cover an achievement of MSS for team sports athletes (Ferro et al., 2014; Vescovi, 2012; Young et al., 2008; Zabaloy, Giráldez, et al., 2021). Conversely, studies investigating trained track and field sprinters revealed an achievement of MSS between 40 and 70 m (Healy et al., 2022; Majumdar & Robergs, 2011). Regarding the intraday reliability of timing gates during 30 – 50-m linear sprints, good absolute and relative reliability was reported (Fornasier-Santos et al., 2022; Helland et al., 2019; Zabaloy, Freitas, et al., 2021; Zabaloy, Giráldez, et al., 2021). Although no studies on interday reliability of assessing MSS with timing gates could be included in this review, studies investigating other sprinting characteristics (e.g., acceleration) confirmed interday reliability of timing gates. Therefore, it can be assumed that interday reliability would be acceptable for MSS as well (Altmann et al., 2019; Haugen et al., 2012). In sum, timing gates with 5- or 10-m split times seem to be a valid and reliable method to assess MSS during linear sprints between 20 and 40 m for team sports with indications that elite sprinters might need longer distances to reach MSS (Ferro et al., 2014; Fornasier-Santos et al., 2022; Healy et al., 2022; Helland et al., 2019; Roe et al., 2017; Vescovi, 2012; Young et al., 2008; Zabaloy, Freitas, et al., 2021; Zabaloy, Giráldez, et al., 2021). However, no results regarding total distances and split times for the examination of MSS with timing gates are available for recreational subjects who might need different distances due to the lack of expertise and lower fitness.

Global and local positioning systems: GPS and LPS have recently become more accessible and affordable to assess running or sprinting characteristics, e.g. MSS. They allow receiving live speed and distance data from multiple subjects simultaneously during testing sessions but also during training or matches (Massard et al., 2018). Regarding the validity of GPS measures during linear sprinting to assess MSS, some of the studies using radar as the reference method (n=6) reported good criterion validity for 10 Hz GPS (three out of four) (Beato et al., 2018; Roe et al., 2017; Sagiroglu et al., 2021). However, Akyildiz et al. (2022) examined rather poor criterion validity for 10 Hz GPS with comparable samples (i.e., male amateur soccer players) and sprinting distances (i.e., 40 m). In addition, 5 Hz and 16 Hz GPS also yielded different results in MSS compared to radar (criterion validity) (Johnston et al., 2012; Lacome et al., 2019). 20 – 45 Hz LPS systems obtained rather poor validity when compared to motion capture (Fleureau et al., 2020; Ogris et al., 2012), indicating that LPS measures are not yet applicable for the assessment of MSS. These results seem surprising as LPS was considered a valid technology to determine other running characteristics, though (Pino-Ortega et al., 2021) point out that validity of LPS is highly dependent on the data processing. Most of the studies (seven out of 10) reported good intraday reliability for MSS assessed with 1 – 20 Hz GPS/LPS (Beato & de Keijzer, 2019; Coutts & Duffield, 2010; Fornasier-Santos et al., 2022; Hoppe et al., 2018; Johnston et al., 2014; Sagiroglu et al., 2021; Willmott et al., 2019) and the one study that assessed interday reliability of 10 Hz GPS showed good absolute reliability (Beato et al., 2018). To conclude, most studies using an accepted gold standard method to assess MSS, i.e. radar technology, could not confirm criterion validity of GPS or showed inadequate methodological quality (four out of six studies) (Akyildiz et al., 2022; Johnston et al., 2012; Lacome et al., 2019; Roe et al., 2017). LPS measurements showed poor criterion and convergent validity in all studies relating to motion capture (n=2) (Fleureau et al., 2020; Ogris et al., 2012). Interday (one out of one study) and intraday reliability (seven out of 10 studies) was reported as good for GPS and LPS in most studies (Beato & de Keijzer, 2019; Beato et al., 2018; Coutts & Duffield, 2010; Fornasier-Santos et al., 2022; Hoppe et al., 2018; Johnston et al., 2014; Sagiroglu et al., 2021; Willmott et al., 2019).

Video analysis *via* smartphone applications: A relatively cheap and easily accessible method to assess sprint kinematics is video analysis via smartphone applications that record time and distance data to calculate for example velocities. Two studies validated a smartphone app (MySprint App) with laser or radar measurements. Results regarding MSS showed good criterion validity in male and female team sport athletes and in male trained sprinters as well as good intraday reliability (Ghigiarelli et al., 2022; Romero-Franco et al., 2017). The results of these two studies investigating a smartphone app indicate that this method can be used validly and reliably to assess MSS; however, with respect to the small number of studies, further investigations are crucial.

Treadmill sprinting: Since MSS is usually measured during linear sprinting on a (outdoor) track, several environmental conditions can influence the outcome measures. Therefore, standardizing by implementing treadmills in the laboratory was previously suggested (Highton et al., 2012). However, the studies examining (non-) motorized treadmills to assess MSS showed poor convergent and criterion validity (large ES) as running on a treadmill yielded much lower MSS than overground running (Highton et al., 2012; Morin & Sève, 2011). This difference is likely a result of the participants having to overcome the high inherent resistance of the treadmill. Though, intraday and interday reliability was reported as good (Highton et al., 2012).

Strengths and limitations

Strengths: The results of this review should be interpreted concerning its limitations and strengths as well as the limitations and strengths of the included studies. A strength of this article is the large number of studies (n=58) that was included in the analysis. In addition, the studies' participants were associated to different backgrounds allowing conclusions for several fitness and settings for adults. A major methodological strength of this review is the application of the COSMIN checklist which is especially suited to evaluate the risk of bias of validity and reliability studies (Mokkink et al., 2020; Mokkink et al., 2018).

Limitations: A limitation is the unequal numbers of studies that could be included for the investigated methods, e.g. only few studies on shuttle runs to estimate MAS or on video analysis to assess MSS. This issue needs to be addressed in the future, so that clearer conclusions can be drawn. Studies in this article can be criticized since a substantial number of studies (50%) used not as gold standard accepted reference methods. Methodological quality of studies reporting validity for the assessment of MSS were mostly rated *inadequate* or *doubtful* (70%). For interday and intraday reliability, 50% of the studies were rated *very good* or *adequate*, and 50% were rated *doubtful* or *inadequate*. These findings can be explained by the inclusion criteria, as there was no restriction on the type of studies. Hence, studies in which validity or reliability assessment for MSS was not the main objective were included as well. Although they were well designed for their main purpose, the information needed for validity or reliability assessment was not always provided. Additionally, many studies reporting validity used very small sample sizes and hence were rated with a low methodological quality. Another limitation of the included studies is the fact that in studies on MAS as well as MSS mostly male participants were used and very few female participants. Moreover, in studies examining MSS mostly team sport athletes were included, potentially because MSS is rather crucial in team sports and sports teams are attractive samples as they usually consist of more than 20 players per team (Haugen & Buchheit, 2016).

Practical applications & Future research

When performance tests are implemented to monitor individual performance changes or to retrieve values for training prescription, these methods have to be highly valid and reliable (Robertson et al., 2017), i.e., with respect to ASR, the methods to assess MAS and MSS. Practitioners and researchers should be aware that the results of methods for CPET to assess MAS indicate that the final speed reached during the test or the speed of the 30-s interval of $\dot{V}O_2max$ are associated with a higher input of anaerobic energy supply than when the speed at the onset of the plateau of VO_2 is determined. Therefore, the speed at the onset of this plateau seem to reflect true MAS and should be assessed (Petot et al., 2012; Thron, Woll, et al., 2022). The results for time trials indicate that distances need to be selected based on the fitness, sex, or type of sports of the participants so that the results for MAS might be valid. We recommend that for subjects with a lower fitness, team sports athletes, or sprinters shorter distances should be used (e.g. 1200 – 1400 m), while longer distances are more favorable for endurance trained athletes to estimate MAS (e.g. 1500 – 2000 m) (Bellenger et al., 2015; Foster et al., 2022; Lundquist et al., 2021; Sandford, Rogers, et al., 2019; Thron, Woll, et al., 2022). In addition, the results for continuous incremental field tests or shuttle runs independently of subjects' fitness (Barbero-Alvarez et al., 2015; Cappa et al., 2014; Čović et al., 2016; Lopes et al., 2015; Pallarés et al., 2019; Thron, Woll, et al., 2022) point out that these tests are not suitable to estimate true MAS.

Besides using radar or laser measurement during linear sprinting (Fornasier-Santos et al., 2022; Simperingham et al., 2019; Zabaloy, Freitas, et al., 2021) timing gates with split times of 5 or 10 m and video analysis with a smartphone application seem promising when determining MSS (Ghigiarelli et al., 2022; Roe et al., 2017; Romero-Franco et al., 2017; Zabaloy, Freitas, et al., 2021). GPS measurements during linear sprinting showed poor validity and the maximal velocities measured during training and matches (Akyildiz et al., 2022; Djaoui et al., 2017; Lacome et al., 2019; Massard et al., 2018; Roe et al., 2017) as well as the maximal speed achieved during treadmill sprinting could not reach the actual MSS (Akyildiz et al., 2022; Djaoui et al., 2017; Highton et al., 2012; Lacome et al., 2019; Massard et al., 2018; Morin & Sève, 2011; Roe et al., 2017). However, to delineate between type of sports, sexes, or fitness, future studies should address population specific validity. From a practical perspective, shorter total distances (20–40 m) are suggested for recreational athletes or type of sports in which shorter sprints are common, e.g. team sports, whereas trained sprinters might need distances between 40 and 70 m to reach MSS (Ferro et al., 2014; Fornasier-Santos et al., 2022; Healy et al., 2022; Helland et al., 2019; Roe et al., 2017; Vescovi, 2012; Young et al., 2008; Zabaloy, Freitas, et al., 2021; Zabaloy, Giráldez, et al., 2021). An overview of the conclusions and practical applications is presented in Figure 5.4.

With respect to controlling training interventions, an example of high-intensity-interval prescriptions with ASR might illustrate the issue of using different methods when assessing the control parameters. When MAS and MSS are retrieved by CPET and radar measurement, respectively, a recreational runner might achieve results of 15 km/h for MAS and 28 km/h for MSS and accordingly an ASR of 13 km/h. However, when for instance the 30-15 IFT is used instead of CPET to set the lower boundary of ASR, the estimated MAS might yield 19 km/h what reduces ASR to 9 km/h (Čović et al., 2016). The prescription of high-intensity-intervals with the intensity of for example 30% ASR (MAS + 30% ASR) will therefore be noticeably more intense with MAS retrieved by the 30-15 IFT than with CPET (i.e., 18.9 km/h for true MAS and 21.7 km/h for 30-15 IFT). Conversely, the intensity would be too low (approx. 18.2 km/h) for the athlete when MSS is assessed for example during matches or training using GPS (Djaoui et al., 2017) (see Figure 5.5). Though, only few studies exist on training interventions using ASR (Julio et al., 2020; Parkes, 2022; Sandford et al., 2021), further research is needed to fill this gap.

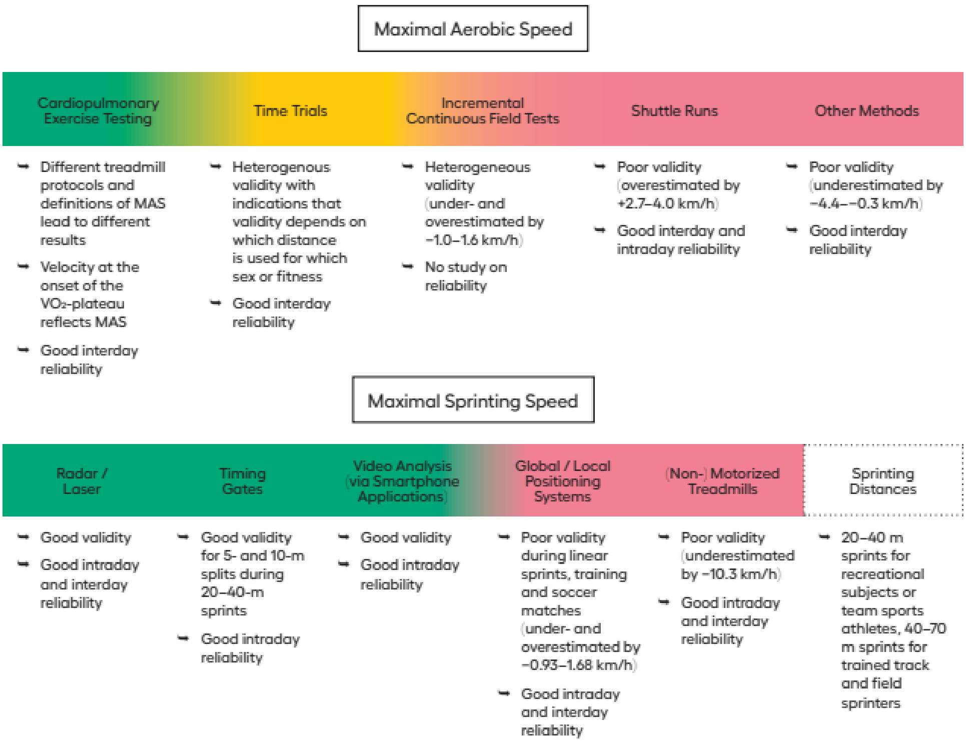

Figure 5.4: Overview of conclusions for the testing methods for maximal aerobic speed and maximal sprinting speed. The color grading reflects the rating for criterion validity – from green indicating good validity to red indicating poor validity. *VO2* Oxygen Uptake, *MAS* Maximal Aerobic Speed.

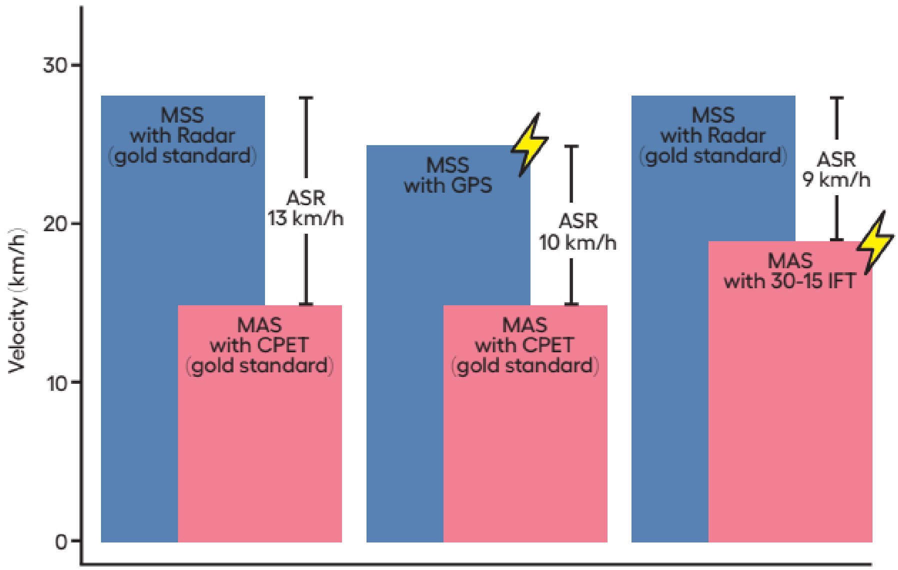

Figure 5.5: Illustration of values for MAS, MAS and ASR when using different testing methods. Presented values are based on the results of Čović et al. (2016) for the MAS data and Djaoui et al. (2017) for the MSS data. When GPS is used, the MSS will most likely be lower compared to radar (approximately 3 km/h). MAS will most likely be higher when the 30-15 IFT is implemented compared to CPET on a treadmill (approximately 4 km/h). The ASR will change accordingly. *MAS* Maximal Aerobic Speed, *MSS* Maximal Sprinting Speed, *ASR* Anaerobic Speed Reserve, *CPET* Cardiopulmonary Exercise Testing, *GPS* Global Positioning System, *30-15 IFT* 30-15 Intermittent Fitness Test.

5.2.6 Conclusion

Beyond assessing single performance parameters, the ASR can provide further insights into an athlete's physiological and neuromuscular profile by considering the individual tolerance to high-intensity exercise. As ASR consists of the parameters MAS and MSS, the methods to assess these parameters need to be valid and reliable.

MAS can be defined during CPET, yet there are different testing protocols without a consensus about the most appropriate one. Due to physiological considerations based on energy supply, the speed at the onset of the VO_2-plateau seems to be the most appropriate method to determine true MAS. For field tests, studies' results on validity are heterogeneous and do not favor a specific field test (incremental continuous or shuttle runs) for the determination of MAS. However, results on time trials indicate that distances adapted to the subjects' sporting background, fitness or sex might be suitable to estimate MAS.

Regarding MSS, linear sprints using timing gates or video analysis seem to provide valid and reliable results besides the gold standard method, i.e. radar or laser measurements. The validity of GPS or sprinting on a treadmill cannot be confirmed. Sprinting distances between 20 and 40 m should be selected for recreational subjects or type of sports in which shorter sprints are crucial, e.g. team sports, whereas trained track and field sprinters might need longer total distances (40 to 70 m) to reach MSS.

In particular the use for prescribing training emphasizes the importance of valid and reliable measurements of MAS and MSS to achieve optimal and desired intensity based on ASR. Methods – ideally with a low measurement error and therefore a high reliability – should be maintained throughout the training routine so that changes in ASR can be attributed to changes in the individual performance and not to differing results because of the testing method.

5.3 Submaximal Predictors of Peak Incremental Running Test Speed (Paper IV)

Currently under review:

Thron, M., Buchheit, M., Ruf, L., Sondermann, Y., Woll, A., & Altmann, S. (under review). Submaximal predictors of peak incremental running test speed as a proxy of maximal aerobic performance in soccer players.

5.3.1 Abstract

Purpose. Peak incremental running test speed (v_{peak}) is a key indicator of aerobic performance, strongly associated with endurance performance and can be used as a benchmark for prescribing high-intensity interval training. This study investigated whether submaximal markers can reliably predict v_{peak} in professional soccer players. **Methods.** N=2648 data points of n=889 highly-trained, male and female soccer players (age range: 12.8–37. years) were included in the analyses. Incremental running tests on a treadmill or Tartan^{TM} track were performed and lactate thresholds (e.g., speed at 4 mmol/L; vL4) and heart rate measures (e.g., submaximal fractional utilization of maximal heart rate; %HRmax12km/h) were assessed. Linear mixed models were calculated to assess potential predictors (i.e., age, sex, vL4, %HRmax12km/h) of v_{peak} and k-fold cross-validation was performed to assess prediction accuracy. **Results.** Among the linear mixed models, the combination of (cubic) age, sex, vL4, and %HRmax12km/h yielded the best predictive performance (conditional R^2: 0.83; root mean squared error (RMSE) of cross-validation: 0.60 km/h). **Conclusion.** This study shows that vL4, age, and sex adequately predict v_{peak} in professional soccer players with a prediction error <0.65 km/h and with

%HRmax12km/h further improving accuracy. These submaximal markers offer a practical alternative to maximal testing for monitoring performance or guiding training.

5.3.2 Introduction

Peak speed attained in an incremental treadmill or field test (v_{peak}) is a widely recognized indicator of aerobic fitness and endurance performance. High correlations between v_{peak} and competitive outcomes in middle- and long-distance running underscore its value as a practical, integrative measure of endurance (Stratton et al., 2009). Also in team sports such as soccer, regular assessment of v_{peak} enables effective tracking of physiological adaptations and performance progression, making it a useful tool in both research and applied settings (Saunders et al., 2010).

Literature indicates that v_{peak} is mainly determined by physiological factors such as the respiratory compensation point (RCP) and maximal oxygen uptake ($\dot{V}O_2max$), with running economy (RE) also contributing as a measure of submaximal efficiency (Alves Pasqua et al., 2016). Furthermore, v_{peak} is closely related to maximal aerobic speed (MAS), the speed at which $\dot{V}O_2max$ occurs, though it typically exceeds MAS by about 2.8% (Thron, Düking, et al., 2024). Given that MAS is a well-established benchmark for prescribing high-intensity interval training, v_{peak} offers a similarly practical reference point, albeit derived differently (Buchheit & Laursen, 2013a). Despite its value, assessing v_{peak} typically requires athletes to perform to physical exhaustion. This can be impractical or undesirable frequent competition or high training loads, such as during a soccer season. In such cases, the use of submaximal markers that are easy to assess and do not require maximal effort could offer a viable alternative for aerobic performance monitoring (Buchheit, Simpson, et al., 2012).

Therefore, the aim of this study was to investigate the potential of submaximal markers such as lactate thresholds or submaximal heart rate, obtained during incremental running tests, to predict v_{peak} as a measure of maximal aerobic performance in professional soccer players. Identifying reliable submaximal predictors could enhance practical monitoring strategies without compromising the validity of performance evaluation.

5.3.3 Methods

Subjects

N=5476 data points of n=1414 highly-trained (tier three and four), male and female soccer players (age range: 12.8–37.6 years) (McKay et al., 2022) initially participated in this study. N=2648 data points of n=889 participants (women N=124, n=51, 22.1±3.1 years, 1.71±0.06 m, 64.4±5.2 kg; men N=2524, n=838, 18.4±4.4 years, 1.76±0.11 m, 70.8±12.5 kg) were included in the analysis after filtering for meeting exhaustion criteria (maximal heart rate (HRmax)≥210-age and peak lactate concentration (Lapeak)≥8.0 mmol/L) and excluding outliers. Data were collected during the routine fitness assessments of the teams so that ethical approval was not required (Winter & Maughan, 2009). All athletes or their legal guardians gave their written informed consent before participation.

Design

In this retrospective study, the athletes performed one or more incremental running tests until physical exhaustion on the treadmill or on a running track.

Methodology

The incremental running test on a treadmill (PPS70; WOODWAY GmbH; Weil am Rhein; Germany) or a Tartan™ track started at 6 km/h (with a constant incline of 1% on the treadmill) and increased every 3 minutes by 2 km/h with 0.5 min rest to collect 20 µL of capillary blood from the right earlobe analyzed using BIOSEN C-Line (EKF Diagnostic; Barleben; Germany) until subjective exhaustion and peak speed (v_{peak}) of the participants. The speed at minimum lactate equivalent (vLT), LT plus 1.5 mmol/L (individual anaerobic threshold; vIAT) as well as at 2 and 4 mmol/L (vL2 and vL4) (Faude et al., 2009) were estimated using the Ergonizer software (Ergonizer, Freiburg, Germany). Submaximal and HRmax were determined using a chest strap (H7 or H10; Polar Electro; Kempele; Finland). Additionally, fractional utilization at 12 km/h of true HRmax (%HRmax12km/h) and theoretical HRmax (=220-age; %theorHRmax12km/h) were calculated for all included athletes.

Statistical Analysis

Statistical analysis was carried out with RStudio (R version 2024.12.0, R Foundation for Statistical Computing, Vienna, Austria) (Team, 2022). Since the data has a hierarchical structure, linear mixed models including restricted maximum likelihood (REML) were calculated using the *lmer* function in the *lme4* package (Bates et al., 2015) with a random intercept per participant, i.e., repeated observations were nested within players. First, it was analyzed if linear, squared, or cubic age best predicts $v_{peak.}$ Considering practical applications, age, sex, test mode (i.e., treadmill or field test), vL2, vL4, vLT, and vIAT were included as predictors. Additionally, %theorHRmax12km/h and %HRmax12km/h were included to compare model fits with and without HR data. For all calculations, the significance level was set at α=0.05 and 95% confidence intervals (CI) as well as root mean squared error (RMSE) were included. Conditional R^2 and Aikake information criterion (AIC) were calculated to assess model fit and marginal R^2 was reported to provide an overview of variance explained by fixed effects. To evaluate model performance on unseen data, 10-fold cross-validation was performed, keeping clustered data within the same fold.

To assess prediction accuracy, RMSE, mean absolute error (MAE), R^2, mean prediction error (bias), Pearson correlation (concordance), and prediction intervals at 80%, 90%, 95%, and 99% were calculated.

5.3.4 Results

The descriptive results related to the athletes' anthropometrics, number of field and treadmill tests, and predictor variables are presented in Appendix 4 Paper IV Supplementary Table 1.

The analyses show that cubic age is a better predictor than squared or linear age (conditional R^2: 0.74, 0.74, and 0.73, respectively; see Appendix 6 Paper IV Supplementary Table 2 (Model 1 and 2) and Figure 5.6); hence, cubic age was added to the following models.

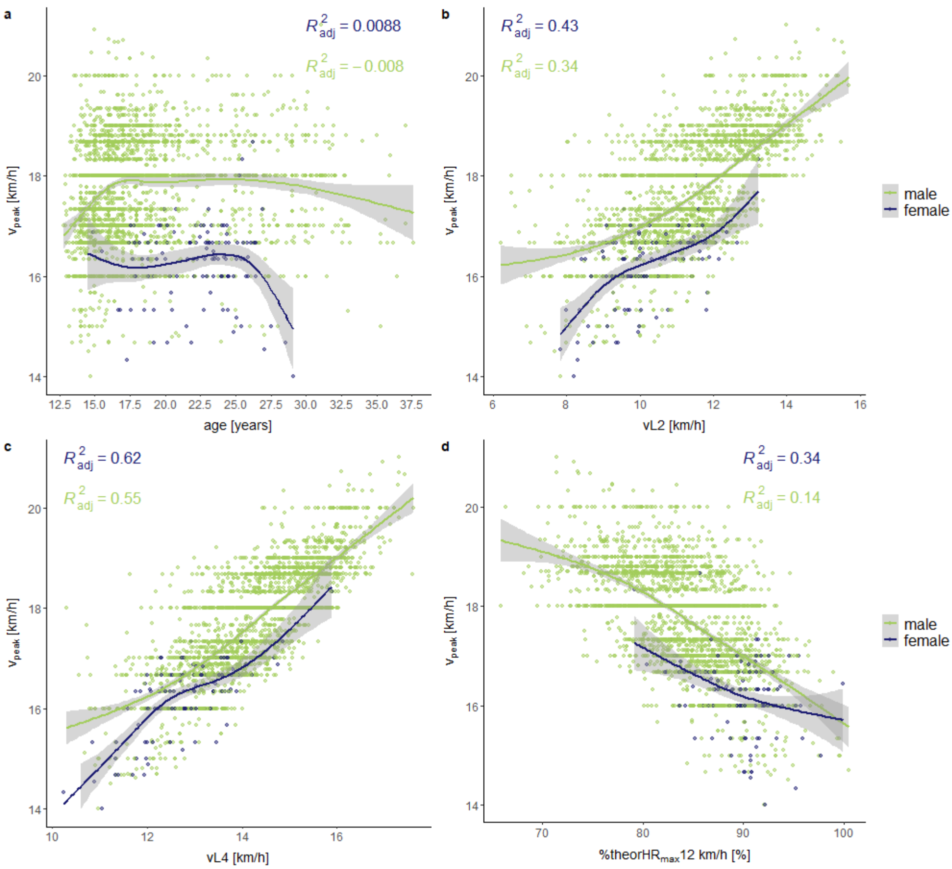

Figure 5.6: Scatterplots with regression lines, 95% confidence interval (grey area), and adjusted R^2 of the association between v_{peak} and age (a), speed at a lactate concentration of 2 mmol/L (vL2) (b), speed at a lactate concentration of 4 mmol/L (vL4) (c), and fractional utilization at 12 km/h of theoretical maximal heart rate (%theorHRmax12km/h) (d). Green lines represent regression lines for men and blue lines for women.

Of the linear mixed models including cubic age, sex and lactate thresholds, the model including vL2 and vL4 shows a slightly better fit than the model including vLT and vIAT (conditional R^2: 0.81 and 0.80, respectively; see Appendix 7 Paper IV Supplementary Table 3 (Model 4 and 5), Figure 5.6 and Appendix 5 Supplementary Figure 1a and b). However, removing vL2 and only adding cubic age, sex, and vL4 to the analysis still provides a good (but slightly poorer) model fit (conditional R^2: 0.80; see Table 5.6, Model 1), while adding test mode improves the fit only marginally (conditional R^2: 0.80; see Table 5.6, Model 2). The cross-validation shows similar prediction accuracies for Model 1 (RMSE: 0.64 km/h; MAE: 0.52 km/h, R^2: 0.66; see Table 5.6) and Model 2 (RMSE: 0.64 km/h; MAE: 0.52 km/h, R^2: 0.66). Therefore, v_{peak} can be estimated using the following equations:

Equation 1 (Model 1):

$$v_{peak} = 1.77433 - 0.72594 * sex + 0.85532 * age - 0.03260 * age^2 + 0.00039 * age^3 + 0.62913 * vL4$$

Equation 2 (Model 2):

$$v_{peak} = 1.72758 - 0.70310 * sex + 0.87962 * age - 0.03354 * age^2 + 0.00040 * age^3 + 0.62215 * vL4 - 0.09145 * mode$$

where sex includes 1 for females and 0 for males, mode includes 1 for treadmill and 0 for field tests, and vL4 represents the speed at a lactation concentration of 4 mmol/L.

Table 5.6: Final models for the association of v_{peak} with vL4, sex and cubic age (model 1) and test mode (model 2).

	Model 1 (N=2648)			Model 2 (N=2648)		
Predictors	**Estimates**	**95% CI**	**p**	**Estimates**	**95% CI**	**p**
(Intercept)	1.77433	-0.03 – 3.58	0.05	1.72758	-0.07 – 3.53	0.06
vL4	0.62913	0.60 – 0.65	<0.001	0.62215	0.60 – 0.65	<0.001
sex [female]	-0.72594	-0.89 – -0.56	<0.001	-0.70310	-0.87 – -0.54	<0.001
age [1st degree]	0.85532	0.60 – 1.11	<0.001	0.87962	0.63 – 1.13	<0.001
age [2nd degree]	-0.03260	-0.04 – -0.02	<0.001	-0.03354	-0.05 – -0.02	<0.001
age [3rd degree]	0.00039	0.0002 – 0.001	<0.001	0.00040	0.0002 – 0.001	<0.001
mode [treadmill]				-0.09145	-0.15 – -0.03	0.002
Random Effects						
σ^2	0.22			0.22		
$\tau_{00\ id}$	0.2			0.2		
ICC	0.49			0.49		
N_{id}	889			889		
Marginal R^2 / Conditional R^2	0.62 / 0.80			0.62 / 0.80		
AIC	4564			4562		
RMSE [km/h]	0.41			0.41		
σ [km/h]	0.46			0.46		
Results of k-fold cross-validation (95% CI)						
RMSE [km/h]		0.64 (0.62 - 0.66)			0.64 (0.62 - 0.66)	
MAE [km/h]		0.52 (0.50 - 0.53)			0.52 (0.50 - 0.53)	
R^2		0.66 (0.64 - 0.68)			0.66 (0.64 - 0.68)	
Bias [km/h]		-0.02 (-0.05 - 0.00)			-0.02 (-0.05 - 0.00)	
Concordance (r)		0.81 (0.80 - 0.82)			0.81 (0.80 - 0.82)	
80% prediction interval		±0.82			±0.82	
90% prediction interval		±1.06			±1.06	
95% prediction interval		±1.26			±1.26	
99% prediction interval		±1.66			±1.65	

CI – confidence interval; p – significance value (bold – $p<0.05$); vL4 – speed at a lactation concentration of 4 mmol/L, σ^2 – sigma, i.e., residual variance; $\tau_{00\ id}$ – tau, i.e., random intercept variance; ICC – intra class correlation coefficient; N_{id} – number of IDs; marginal or conditional R^2 – coefficient of determination for fixed or random effects, respectively; AIC – Akaike information criterion; RMSE – root mean squared error; σ – residual standard deviation; MAE – mean absolute error; bias – mean prediction error; r – Pearson's r.

The linear mixed model analyses including cubic age, sex, and HR data show that %HRmax12km/h (i.e., submaximal HR as percentage of HRmax) is a better predictor than %theorHRmax12km/h (i.e., submaximal HR as percentage of theoretical HRmax) (conditional R^2: 0.79 and 0.76, respectively, see Table 5.7, Models 3 and 4). Further adding vL4 improves the fit to the best model fit (conditional R^2: 0.83, see Table 5.7) and accuracy of prediction overall (RMSE: 0.60 km/h; MAE: 0.48 km/h, R^2: 0.70; see Table 5.7, Model 5). Therefore, v_{peak} can be predicted using the following equations:

Equation 3 (Model 3):

$$v_{peak} = 19.76100 - 0.91153 * sex + 0.88592 * age - 0.03731 * age^2 + 0.00049 * age^3 - 0.10346 * \%theorHRmax12km/h$$

Equation 4 (Model 4):

$$v_{peak} = 23.52639 - 0.72566 * sex + 0.78180 * age - 0.03302 * age^2 + 0.00043 * age^3 - 0.13649 * \%HRmax12km/h$$

Equation 5 (Model 5):

$$v_{peak} = 7.30931 - 0.60047 * sex + 0.78479 * age - 0.03085 * age^2 + 0.00038 * age^3 - 0.04014 * \%theorHRmax12km/h + 0.52905 * vL4$$

Equation 6 (Model 6):

$$v_{peak} = 11.88180 - 0.49297 * sex + 0.70940 * age - 0.02822 * age^2 + 0.00035 * age^3 - 0.07364 * \%HRmax12km/h + 0.45893 * vL4$$

where sex includes 1 for females and 0 for males, vL4 represents the speed at a lactation concentration of 4 mmol/L, %theorHRmax12km/h represents fractional utilization at 12 km/h of theoretical HRmax (220 – age), and %HRmax12km/h represents fractional utilization at 12 km/h of true HRmax.

Table 5.7: Final models for the association of vpeak with sex, cubic age with %theorHRmax12km/h (Model 3), %HRmax12km/h (Model 4), %theorHRmax12km/h and vL4 (Model 5), and %HRmax12km/h and vL4 (Model 6).

	Model 3 (N=2648)			Model 4 (N=2648)			Model 5 (N=2648)			Model 6 (N=2648)		
Predictors	**Estimates**	**95% CI**	**p**	**Estimates**	**95% CI**	**p**	**Esti-mates**	**95% CI**	**p**	**Estimates**	**95% CI**	**p**
(Intercept)	19.76100	17.45 – 22.07	<0.001	23.52639	21.38 – 25.68	<0.001	7.30931	5.34 – 9.27	<0.001	11.88180	9.96 – 113.80	<0.001
sex [female]	-0.91153	-1.14 – -0.69	<0.001	-0.72566	-0.93 – -0.52	<0.001	- 0.60047	-0.76 – -0.44	<0.001	-0.49297	-0.65 – -0.34	<0.001
age [1st degree]	0.88592	0.57 – 0.20	<0.001	0.78180	0.50 – -1.07	<0.001	0.78479	0.54 – 1.03	<0.001	0.70940	0.47 – 0.94	<0.001
age [2nd degree]	-0.03731	-0.05 – -0.02	<0.001	-0.03302	-0.05 – -0.02	<0.001	- 0.03085	-0.04 – -0.02	<0.001	-0.02822	-0.04 – -0.02	<0.001
age [3rd degree]	0.00049	0.0003 – 0.0007	<0.001	0.00043	0.0002 – 0.0006	<0.001	0.00038	0.0004 – 0.001	<0.001	0.00035	0.0002 – 0.001	<0.001
%theorHRmax12km/h	-0.10346	-0.11 – -0.10	<0.001				- 0.04014	-0.05 – -0.03	<0.001			
%HRmax12km/h				-0.13649	-0.14 – -0.13	<0.001				-0.07364	-0.08 – -0.07	<0.001
vL4							0.52905	0.50 – 0.56	<0.001	0.45893	0.43 – 0.49	<0.001
Random Effects												
σ^2	0.26			0.23			0.20			0.18		
$\tau_{00\ id}$	0.45			0.35			0.19			0.18		
ICC	0.63			0.61			0.48			0.49		
N_{id}	889			889			889			889		
Marginal R^2 / Conditional R^2	0.35 / 0.76			0.46 / 0.79			0.64 / 0.81			0.67 / 0.83		
AIC	5438			5028			4430			4170		
RMSE [km/h]	0.44			0.42			0.40			0.38		
σ [km/h]	0.51			0.48			0.45			0.43		
Results of k-fold cross-validation (95% CI)												
RMSE [km/h]		0.86 (0.83 - 0.88)			0.77 (0.75 - 0.79)			0.63 (0.61 - 0.65)			0.60 (0.59 - 0.62)	
MAE [km/h]		0.69 (0.67 - 0.71)			0.61 (0.60 - 0.63)			0.51 (0.49 - 0.52)			0.48 (0.47 - 0.49)	

R^2	0.39 (0.36 - 0.41)			0.51 (0.48 - 0.53)			0.67 (0.65 - 0.69)			0.70 (0.68 - 0.72)	
Bias [km/h]	-0.08 (-0.11 - - 0.04)			-0.06 (-0.09 - - 0.03)			-0.03 (-0.06 - -0.01)			-0.03 (-0.05 - - 0.01)	
Concordance (r)	0.62 (0.60 - 0.64)			0.71 (0.69 - 0.73)			0.82 (0.81 - 0.83)			0.84 (0.82 - 0.85)	
80% prediction interval	±1.10			±0.99			±0.81			±0.77	
90% prediction interval	±1.41			±1.27			±1.04			±0.99	
95% prediction interval	±1.68			±1.51			±1.24			±1.18	
99% prediction interval	±2.21			±1.99			±1.62			±1.55	

CI – confidence interval; p – significance value (bold – $p<0.05$); %theorHRmax12km/h – fractional utilization at 12 km/h of theoretical maximal heart rate, i.e. 220 - age; %HRmax12km/h - fractional utilization at 12 km/h of maximal heart rate; vL4 – speed at a lactation concentration of 4 mmol/L, σ^2 – sigma, i.e., residual variance; $\tau_{00\ id}$ – tau, i.e., random intercept variance; ICC – intra class correlation coefficient; N_{id} – number of IDs; marginal or conditional R^2 – coefficient of determination for fixed or random effects, respectively; AIC – Akaike information criterion; RMSE – root mean squared error, σ – residual standard deviation; MAE – mean absolute error; bias –mean prediction error; r – Pearson's r.

5.3.5 Discussion

Discussion of Results

This study aimed to investigate the potential of submaximal markers, obtained during incremental running tests, to predict v_{peak} as a proxy of maximal aerobic speed in a large sample of professional soccer players. According to our results (Equation 1; Table 5.6), fixed lactate thresholds (e.g., vL4) together with cubic age and sex are strong predictors of v_{peak}, regardless of test mode. Adding fractional utilization of HRmax at a submaximal speed (%theorHRmax12km/h or %HRmax12km/h) further improves model fit, reducing prediction error to <0.86 km/h (Equation 3, 4, 5, and 6; Table 5.7).

The strong association between vL4 and v_{peak} aligns with previous studies (Alves Pasqua et al., 2016; Peyré-Tartaruga et al., 2024). The fact that vL4 as a percentage of v_{peak} has a standard deviation of 80.3±4.11% (see Appendix 4 Paper IV Supplementary Table 1) indicates that our sample is homogeneous, allowing for accurate prediction. Moreover, increased mitochondrial density and enzymatic activity contribute to reduced metabolic acidosis, enabling athletes to sustain higher speeds or cover greater distances without compromising oxidative metabolism, ultimately supporting a higher v_{peak} (Peyré-Tartaruga et al., 2024). Additionally, since oxidative capacity declines with age and is generally lower in women than men, it is coherent that v_{peak}, which is closely linked to aerobic performance, shows similar age- and sex-related differences (Peyré-Tartaruga et al., 2024). Considering that sex, age, and vL4 explain 80% of the model variance and the average prediction error (cross-validation) is 0.64 km/h, Equation 1 provides an adequate estimation of v_{peak}.

Adding %HRmax12km/h increases explained variance to 83% with a reduced prediction error of 0.60 km/h. Since submaximal HR decreases with higher running speeds in incremental tests, a lower fractional utilization of HRmax at submaximal intensities reflects better aerobic performance (Buchheit, Simpson, et al., 2012) and thus higher v_{peak}.

Practical Applications

The present findings have important practical implications for aerobic performance testing and monitoring in professional soccer. Practitioners can use submaximal markers such as vL4 alongside sex and age as reliable, accessible predictors of v_{peak} regardless of whether testing in the field or on a treadmill (Equation 1). Even if lactate thresholds are unavailable, using submaximal fractional utilization of HRmax (Equation 4), which could be derived from training or match data, or estimated HRmax (Equation 3) allows for (see RMSE of cross-validation) v_{peak} estimations smaller than the typical smallest worthwhile change for v_{peak} or MAS of 1 km/h (Buchheit & Laursen, 2013). An online calculator can be assessed here (Chang et al., 2012): https://vpeak.shinyapps.io/vpeak_prediction/

In addition to testing and monitoring, these estimations can serve as benchmarks for (high-intensity interval) training prescription. However, since v_{peak} is protocol-dependent, these estimations relate specifically to increments of 2 km/h and 3 min stages. For broader application, predictors of v_{peak} using other protocols and athlete populations need to be addressed in future research.

5.3.6 Conclusion

This study demonstrates that submaximal markers, particularly vL4, combined with age and sex, are strong predictors of v_{peak} as an indicator of aerobic performance in professional soccer players. The addition of fractional heart rate utilization at submaximal speed further enhances model accuracy. These findings support the use of submaximal, easily obtainable physiological markers to estimate v_{peak}, offering a practical and efficient approach for monitoring aerobic performance or prescribing high-intensity interval training.

6 Acute Responses and Chronic Adaptations Related to the Locomotor Profile (Papers V + VI)

6.1 Locomotor Profile and Acute Responses (Paper V)

Published as:

Thron, M., Ruf, L., Buchheit, M., Härtel, S., Woll, A., & Altmann, S. (2024). Anaerobic speed reserve and acute responses to a short-format high-intensity interval session in runners. *Journal of Science and Medicine in Sport*.
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6.1.1 Abstract

Objectives. This study aimed to assess relationships of acute responses to short-format high-intensity interval training (HIIT) with the anaerobic speed reserve (ASR) of adolescent runners. **Design.** Pre-post intervention design. **Method.** Eighteen highly-trained youth runners (15.83±0.86 years) underwent maximal sprinting speed (MSS) and maximal aerobic speed (MAS) assessments to determine ASR (MSS minus MAS) and a standardized HIIT protocol (2x(20x15s/15s @110% MAS)) was administered. Pre/post-HIIT assessments included biochemical (i.e., creatine kinase (CK)), neuromuscular (countermovement jump; CMJ; reactive strength index, RSI), cardiac (i.e., heart rate recovery (HRR)), and athlete-reported outcome measures (e.g., single item for fatigue). Pearson' r was calculated to assess relationships between acute responses and ASR, MSS, MAS, and relative intensity of the HIIT (%ASR). **Results.** Athletes' ASR an %ASR were significantly associated with the pre/post difference of CK ($r=-0.75$; $p<0.001$; $r=0.74$; $p<0.001$, respectively), CMJ height, and RSI ($r\geq0.69$; $p\leq0.002$; $r\leq-0.49$; $p\leq0.04$, respectively). However, HRR did not correlate significantly with ASR or %ASR ($r\leq0.37$, $p\geq0.131$, $r\geq-0.31$; $p\geq0.22$, respectively). The pre/post difference of RSI correlated with MAS ($r=-0.54$; $p=0.02$), and the pre/post difference of CK ($r=-0.50$; $p=0.034$) and of CMJ height ($r=0.76$; $p<0.001$) with MSS. Regarding athlete-reported measures, ASR and %ASR showed significant associations with most fatigue and recovery variables ($r\geq0.57$; $p\leq0.014$, $r\geq0.57$; $p\leq0.013$, respectively). The pre/post difference of the single item for fatigue showed a positive relationship with MSS ($r=0.49$; $p=0.037$). **Conclusions.** Acute biochemical, neuromuscular, and

athlete-reported responses to short-format HIIT showed strong relationships with ASR and MSS, indicating higher internal load in athletes with a lower ASR and MSS by using a higher %ASR, compared to athletes with a higher ASR and MSS. These findings can help to tailor training programs to individual needs and avoid possible overload.

6.1.2 Introduction

High-intensity running is a common requirement in competitive sports, demanding an integration of various metabolic systems as well as neuro-mechanical capabilities. The ability to perform and cope with high-intensity interval training (HIIT) is thus crucial in most running-based sports such as sprinting, middle-distance running, or team sports (Cipryan et al., 2017).

However, the tolerance towards HIIT is dependent on different factors such as muscle fiber type distribution (Lievens et al., 2020) or cardiorespiratory and metabolic capacities as determined by for example the maximal oxygen uptake ($\dot{V}O_2max$) or the first velocity at $\dot{V}O_2max$, i.e., the maximal aerobic speed (MAS) (Cipryan et al., 2017). While the $\dot{V}O_2max$ and MAS are limited to describing aerobic, oxidative capacities and performances, the anaerobic speed reserve (ASR) reflects the difference between MAS and the maximal sprinting speed (MSS) which incorporates neuro-mechanical, coordinative and glycolytic capabilities. Thus, it was previously suggested that athletes can be categorized in different locomotor profiles, i.e., athletes with a high ASR, high MSS, and low MAS are referred to as sprint types, athletes with a low ASR, low MSS, and high MAS as endurance types, and athletes with a moderate ASR, moderate MSS, and moderate MAS as hybrid types (Buchheit & Laursen, 2013a; Sandford et al., 2021). Additionally, the ASR is increasingly used for prescribing HIIT and has shown to result in more homogeneous chronical adaptations across team sport athletes (Dai & Xie, 2023; Wang & Ye, 2024) and acute adaptations across team sports athletes and runners compared to MAS-prescribed HIIT (Collison et al., 2022; Julio et al., 2020). Furthermore, it is assumed that the ASR together with its components (i.e., MAS and MSS) is a good predictor for the individual tolerance to HIIT (Buchheit, Hader, et al., 2012).

These assumptions are based on a previous study showing that running time to exhaustion during different high-intensity runs based on MAS is better explained by the percentage of ASR used during that run than the percentage of MAS indicating that the ASR may be a better predictor for tolerance to high-intensity exercise than the MAS (Blondel et al., 2001). In contrast, Buchheit, Hader, et al. (2012) found that a higher amount of completed sets of a HIIT until exhaustion by different recreational team sports players is associated with a higher $\dot{V}O_2max$ and MAS, while the ASR only has an influence if adjusted for differences in MAS. These results highlight the importance of considering the underpinning qualities of MAS and MSS in addition to the ASR when explaining differences in acute responses or performance differences. Besides considering performance outcomes such as time to exhaustion, acute responses such as cardiorespiratory (e.g., time spent at or near $\dot{V}O_2max$, maximal heart rate), biochemical (e.g., creatine kinase (CK), blood lactate concentration), neuromuscular (e.g., jumping performance), and acute athlete-reported outcomes (e.g., rating of perceived exertion (RPE)) can be helpful in evaluating the individual tolerance to HIIT (Buchheit, Hader, et al., 2012; Buchheit & Laursen, 2013a; Cipryan et al., 2017; Seiler & Sylta, 2017). Additionally, the heart rate recovery (HRR) after an exercise was previously used as an indirect and further measure of acute load, because it is associated with blood lactate accumulation and muscle acidosis (Buchheit et al., 2010).

In the context of ASR, a lower MAS and a higher percentage of ASR used during repeated sprinting led to a higher blood lactate concentration after and percentage used of $\dot{V}O_2max$ during HIIT, while the athletes' MSS did not affect these acute responses (Buchheit, Hader, et al., 2012). Additionally, the heart rate recovery (HRR) after repeated sprinting seems to be associated with the ASR in athletes of different disciplines, however, these results are inconclusive due to sex differences (Del Rosso et al., 2017). Interestingly and in contrast, athletes from a sprint or endurance background did not show differences in acute responses to short and long format HIIT based on MAS related to the cardiac autonomic regulation, inflammation, or muscle damage (Cipryan et al., 2017). Regarding athlete-reported outcome measures after short- or long-format HIIT or after repeated sprinting, RPE seems to not be influenced by the locomotor profile (i.e., ASR, MAS, and MSS) (Buchheit, Hader, et al., 2012) or the type of runner (i.e., endurance versus sprint athletes, based on the targeted competition) (Cipryan et al., 2017).

While individualization of HIIT based on profiling could enhance training processes by applying the optimal degree of external load (Dai & Xie, 2023), knowledge about the individual tolerance to HIIT could provide additional information for the optimal prescription of HIIT, e.g. to avoid overload. Since several studies previously reported more homogeneous adaptations based on ASR-prescribed HIIT compared to MAS-based HIIT, we assume that individual locomotor profiles (i.e., characterized based on ASR, MAS, and MSS) are related to acute responses to MAS-based HIIT. However, in practice, MAS-based prescription of HIIT is still very commonly used, as it represents one way to normalize the intensity of HIIT. Therefore, we aimed to assess associations of acute cardiorespiratory, neuromuscular, biochemical, and athlete-reported fatigue, stress, and recovery responses to short-format HIIT normalized according to MAS with the ASR and its components (i.e., MAS and MSS) in adolescent runners.

6.1.3 Methods

Participants

In this study, N=18 adolescent female and male (female n=7; weight 59.21±8,21 kg; height 1.75±0.08 m; age 15.83±0.86 years; training 8.64±2.65 hours per week; expertise 7.22±2.92 years of systematic training; $\dot{V}O_2max$ 55.17±4.08 mL/min/kg) 400-m and middle-distance runners classified as tier three athletes (highly-trained) (McKay et al., 2022) and familiar with HIIT were included. This study was approved by the local ethics committee (Approval Number: 22-10). The participants and their legal guardians were informed about the procedures and possible risks and agreed to participate by signing a consent form.

Design

The participants completed the different measures at two different visits. At their first visit, each athlete underwent a standardized warm-up before they conducted two 60-m sprints with 20-min rest to assess the MSS (= the fastest sprinting speed out of the two sprints). Following a 30-min passive rest, the participants performed a cardiopulmonary exercise test (CPET) on a treadmill to assess the MAS and $\dot{V}O_2max$. On a second visit after two to five weeks, the participants conducted a short-format HIIT while several measurements pre (biochemical, neuromuscular, cardiac, and athlete-reported fatigue, stress, and recovery measures), during (cardiopulmonary measures), post (biochemical, neuromuscular, cardiac, and athlete-reported fatigue, stress, and recovery measures), and 24-h delayed (athlete-reported fatigue, stress, and recovery measures) were performed to determine the individual responses to the HIIT.

Methodology

Sprint Testing: The 60-m sprints were implemented either on an outdoor or indoor Tartan™ track depending on the available location of the athletes. The athletes started sprinting in a standing position with a self-timed start and the velocity was continually recorded with a radar gun (Stalker ATS II; 46.875 Hz; Richardson; USA) (Thron, Düking, et al., 2024). The radar gun was placed on a waist-high tripod two meters behind the start. The data were first processed with the manufacturer’s software. Using a custom-made R Studio (Team, 2022) script, speed-time curves were then fitted by a biexponential function to calculate MSS (Morin et al., 2006).

Cardiopulmonary Exercise Testing: The CPET on a treadmill (PPSmed 55, PPSmed L70, 4front, or ST 4front; WOODWAY GmbH; Weil am Rhein; Germany) started at 8 km/h with a constant incline of 1% and increased every minute by 1 km/h until subjective exhaustion of the participants (Billat et al., 1996). Breath-by-breath ventilatory data were obtained using the Metalyzer 3B or MetaMax 3 spirometer (Cortex Biophysik GmbH; Leipzig; Germany). A 15-second moving average filter was used for further analysis (Vogler et al., 2010). Gas sensors were calibrated using gases of known concentrations (15% O_2, 5% CO_2), and the turbine volume transducer was calibrated using a 3-l syringe (Cortex Biophysik GmbH; Leipzig; Germany). The $\dot{V}O_2$-data were first examined for a plateau which is defined as a lower increase in $\dot{V}O_2$ than 150 ml/min in the last minute of exercise (Thron, Woll, et al., 2022); $\dot{V}O_2max$ was assessed as the highest 30-s-interval of $\dot{V}O_2$ (Nolte et al., 2023). Physical exhaustion and thus $\dot{V}O_2max$ were checked using several parameters: The highest respiratory exchange ratio (RER_{end}; quotient of $\dot{V}CO_2$/ $\dot{V}O_2$) at the end of the exercise, maximal heart rate (HRmax) using a chest strap (H7 or H10; Polar Electro; Kempele; Finland), and session ratings of perceived exertion (sRPE; scale 6 – 20) after test termination. Immediately et the end, 3 min, and 5 min after the test, 20 µL of capillary blood was collected from the right earlobe to assess the maximal lactate concentration after the treadmill test (La_{max}) and analyzed using the BIOSEN C-Line (EKF Diagnostic; Barleben; Germany). Confirmation of physical exhaustion required meeting at least two of the following criteria: $RER_{end} \geq 1.0$; sRPE $\geq$ 17; HRmax $\geq$ 210-age, $La_{max} \geq$ 8 mmol/L, and reaching a $\dot{V}O_2$-plateau. The MAS represents the first (interpolated) velocity when reaching this plateau (Thron, Düking, et al., 2024; Thron, Woll, et al., 2022).

ASR was determined as the speed difference between MSS and MAS. For further describing the sample, the speed reserve ratio (SRR) was quantified as the quotient of MSS and MAS.

High-Intensity Interval Session: On a treadmill, the participants performed a warm-up of two minutes at 70% MAS and three minutes at 90% MAS. Immediately after the warm-up, the participants underwent a HIIT consisting of two sets with 20 repetitions of running 15 s at 110% of the individual MAS and 15 s of passive rest (Bok, Gulin, Škegro, et al., 2023). In between sets, the participants rested for 2 min. The participants' breath-by-breath ventilatory data were again obtained using the the Metalyzer 3B or MetaMax 3 spirometer and a 15-s moving average filter. The HR was recorded using a chest strap. To check the participants' cardiorespiratory load during the HIIT, the times spent >90% of HRmax (t90%HRmax) and >90% of $\dot{V}O_2max$ (t90%$\dot{V}O_2max$) were assessed (Bok, Gulin, & Gregov, 2023; Buchheit & Laursen, 2013a).

Biochemical, Neuromuscular, Cardiac, and Athlete-Reported Measures: Thirty minutes prior to and after the HIIT, 20 µL of capillary blood was collected from the fingertip and analyzed with the SimplexTAS™ 101 Analyser (TASCOM; Gyeonggi-do, Korea) to assess plasma creatine kinase (CK) activity. In addition, the participants performed three countermovement jumps (CMJ) to assess maximal CMJ height and three drop jumps (DJ; 30 cm height) to assess the maximal reactive strength index (RSI=jump height/contact time) on a Hawkin Dynamics, Inc. force plate (Westbrook, Maine, USA) (Badby et al., 2023) ten minutes before and after the HIIT. To monitor the cardiac response, the HRR was documented from the end to one minute post (HRR1’) and from one minute post to two minutes post HIIT (HRR2’). Additionally, the participants completed the Short Recovery and Stress Scale (SRSS) consisting of four dimensions each regarding recovery (physical performance capability, mental performance capability, emotional balance, and overall recovery) and stress (muscular stress, lack of activation, negative emotional state, and overall stress) pre and post HIIT. The rating scale ranged from 0 (does not apply at all) to 6 (fully applies) (Kölling et al., 2020). The participants answered a single item for fatigue rated on a bipolar response option (-3=much worse than normal; 0=normal; +3=much better than normal) (Van Hooff et al., 2007) and the sRPE before and immediately after the HIIT. The SRSS and the single item for fatigue were additionally assessed 24 h after the HIIT.

Statistical Analysis

Statistical analysis was carried out with RStudio (R version 4.3.2, R Foundation for Statistical Computing, Vienna, Austria) (Team, 2022). The Pearson's correlation coefficient was calculated to detect relationships between the pre/post changes in the acute responses variables and the predictors variables ASR, MAS, MSS, the relative portion of ASR during the HIIT (%ASR), and $\dot{V}O_2max$, and between ASR and the anthropometrics, MAS, MSS, $\dot{V}O_2max$, and the cardiopulmonary responses during the HIIT using the ‘cor.test’ function in the ‘stats’ package (Team, 2022). According to Hopkins (2004), the magnitude of the correlation was considered to be small ($0.1 \leq r < 0.3$), medium ($0.3 \leq r < 0.5$), large ($0.5 \leq r < 0.7$), very large ($0.7 \leq r < 0.9$), and almost perfect ($r \geq 0.9$) classifications. For an additional analysis of differences in acute responses between athletes with a high and low ASR (using k-means clustering), a two-way analysis of variance was conducted (see Appendices 8-16) For all calculations, the significance level was set at $\alpha=0.05$ and 95% confidence intervals (CI) were included.

6.1.4 Results

Descriptive Results

The descriptive results related to the anthropometrics, CPET and sprinting outcomes, and the cardiovascular responses during the HIIT are presented in Table 6.1. MSS (r=0.79), SRR (r=0.89), and %ASR for the intensity during the HIIT (r=-0.92) showed very large to almost perfect relationships with the ASR.

Results for Biochemical, Neuromuscular, and Cardiac Response

The cardiorespiratory responses during the HIIT, i.e., t90%HRmax and t90%$\dot{V}O_2max$, did not show any relationships with ASR (see Table 6.1). The relationships between the pre/post differences of the acute responses and ASR, MAS, MSS, and %ASR are presented in Figure 6.1, 6.2, 6.3, and 6.4 respectively, and a descriptive visualization of the association of the pre/post differences with MAS and MSS is shown in Figure 6.2. The pre/post difference of CK showed a very large relationship with ASR (r=-0.75 see Figure 1). In addition, large to very large correlations were found between the pre/post difference in CMJ height (r=0.69) and in RSI (r=0.79) and the ASR. However, the HRR and the ASR did not correlate (r≤0.37). Regarding the relative intensity of the HIIT, medium to very large associations were found between the pre/post differences of CK (r=0.74), CMJ height (r=-0.49), and RSI (r=-0.84) and the %ASR. The pre/post differences of any of the objective variables did not correlate with $\dot{V}O_2max$ (r≤0.33; see Appendix 16 Supplementary Figure 2), whereas the pre/post difference of RSI showed a negative relationship with MAS (r=-0.54, see Figures 6.2 and 6.4) and MSS (r=-0.50; see Figures 6.3 and 6.4). The pre/post difference of CMJ height showed a positive correlation with MSS (r=0.76).

Table 6.1: Descriptive results of anthropometrics, CPET and sprinting outcomes, and cardiovascular response during the HIIT and relationships of these variables with the ASR.

	Age [years]	**Mass [kg]**	**Height [m]**	**WA scores**	**$\dot{V}O_2max$ [mL/min/kg]**	**MAS [km/h]**	**MSS [km/h]**	**ASR [km/h]**	**SRR**	**110%MAS [km/h]**	**%ASR**	**T90% $\dot{V}O_2max$ [s]**	**T90% HRmax [s]**
	mean±SD (min–max)												
N=18	**15.89±0.76 (15.00–17.00)**	**59.00±8.00 (45.00–70.00)**	**1.75±0.08 (1.62–1.89)**	**799±92 (598–887)**	**55.20±4.10 (47.00–63.00)**	**16.17±1.58 (12.50–19.25)**	**31.67±2.44* (27.14–35.85)**	**15.50±2.48 (10.89–19.60)**	**1.91±0.21* (1.62–2.38)**	**17.78±1.73 (13.75–21.18)**	**10.74±2.22* (6.92–14.92)**	**43±46 (0–195)**	**1,046±136 (800–1,200)**

CPET – cardiopulmonary exercise testing; MAS – maximal aerobic speed; MSS – maximal sprinting speed; ASR – anaerobic speed reserve; SRR – speed reserve ratio; $\dot{V}O_2max$ – relative maximal oxygen update; %ASR – 110%MAS, i.e., intensity of high-intensity interval training (HIIT), relative to ASR; T90% $\dot{V}O_2max$ – time spent above 90% of $\dot{V}O_2max$ during HIIT, T90% HRmax – time spent above 90% of HRmax during HIIT; SD – standard deviation; min – minimum; max – maximum; WA-scores – scores based on the World Athletic scoring system; * indicates $p<0.001$, i.e., significant correlation with ASR.

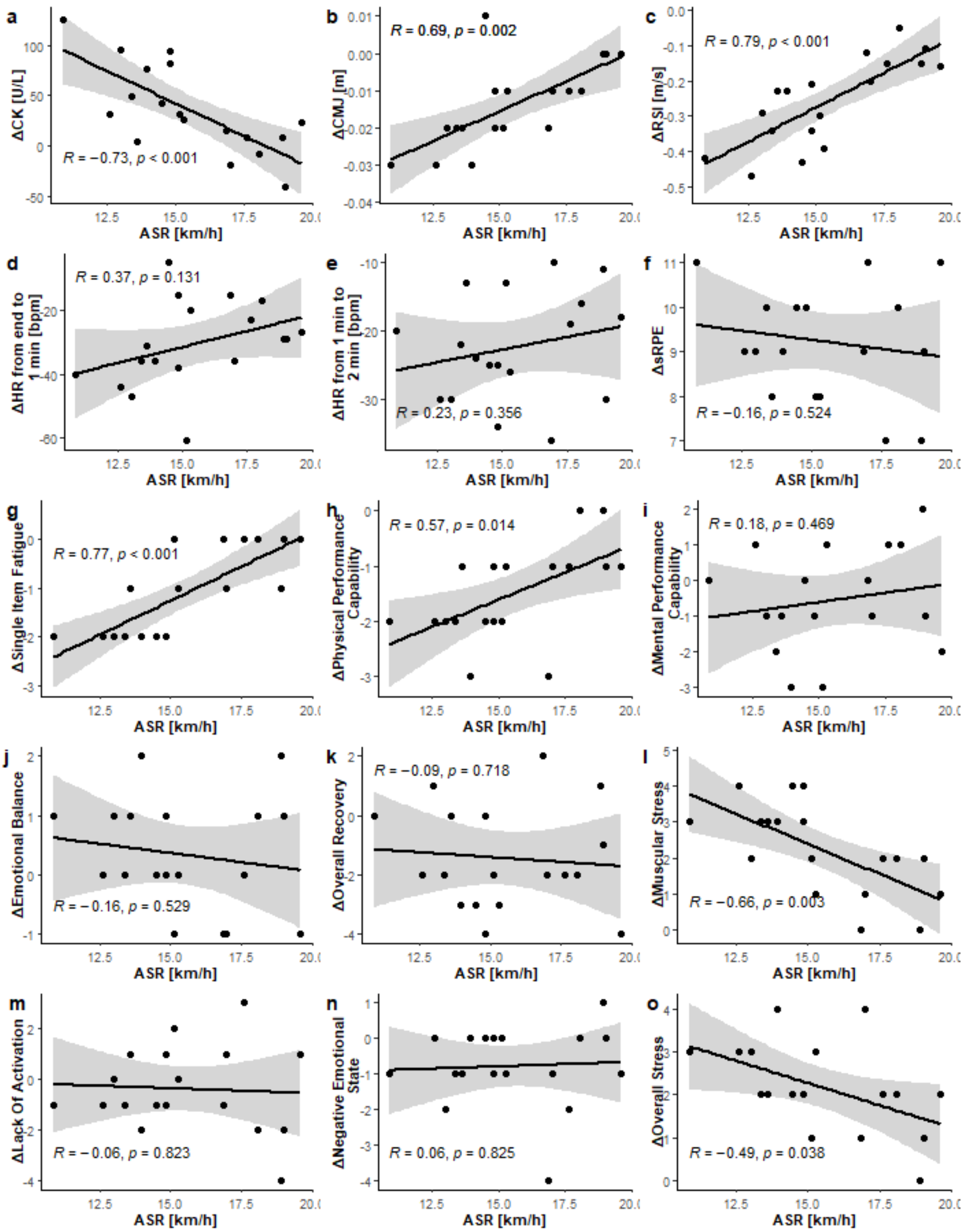

Figure 6.1: Scatterplots with regression lines and 95% confidence intervals (grey area) for ASR with the different objective and athlete-reported variables. ASR – Anaerobic Speed Reserve; Δ – Delta, i.e., pre/post difference; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion; r – Pearson's r; p – significance value.

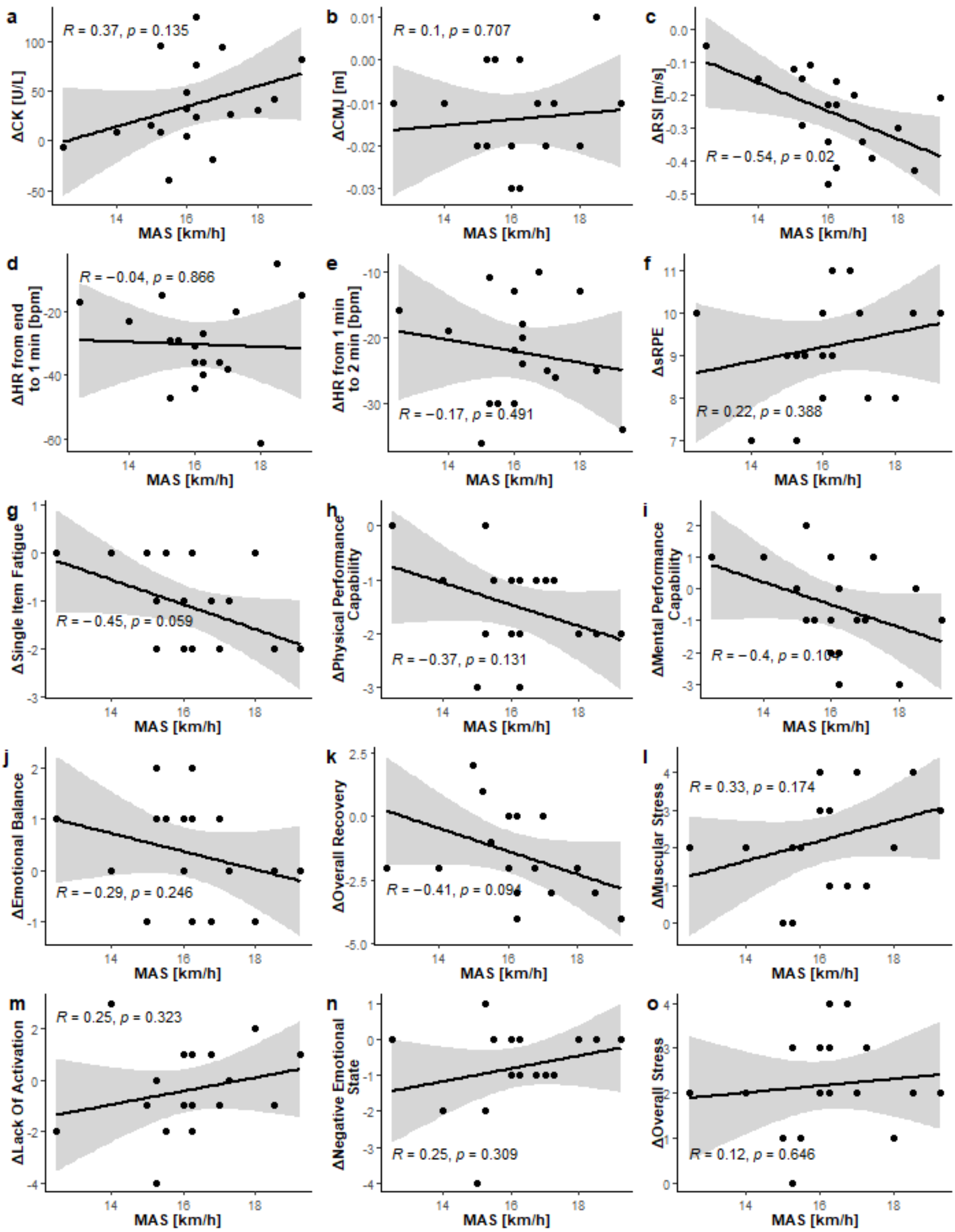

Figure 6.2: Scatterplots with regression lines and 95% confidence intervals (grey area) for MAS with the different objective and athlete-reported variables. MAS – Maximal Aerobic Speed; Δ – Delta, i.e., pre-post difference; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion; r – Pearson's r; p – significance value.

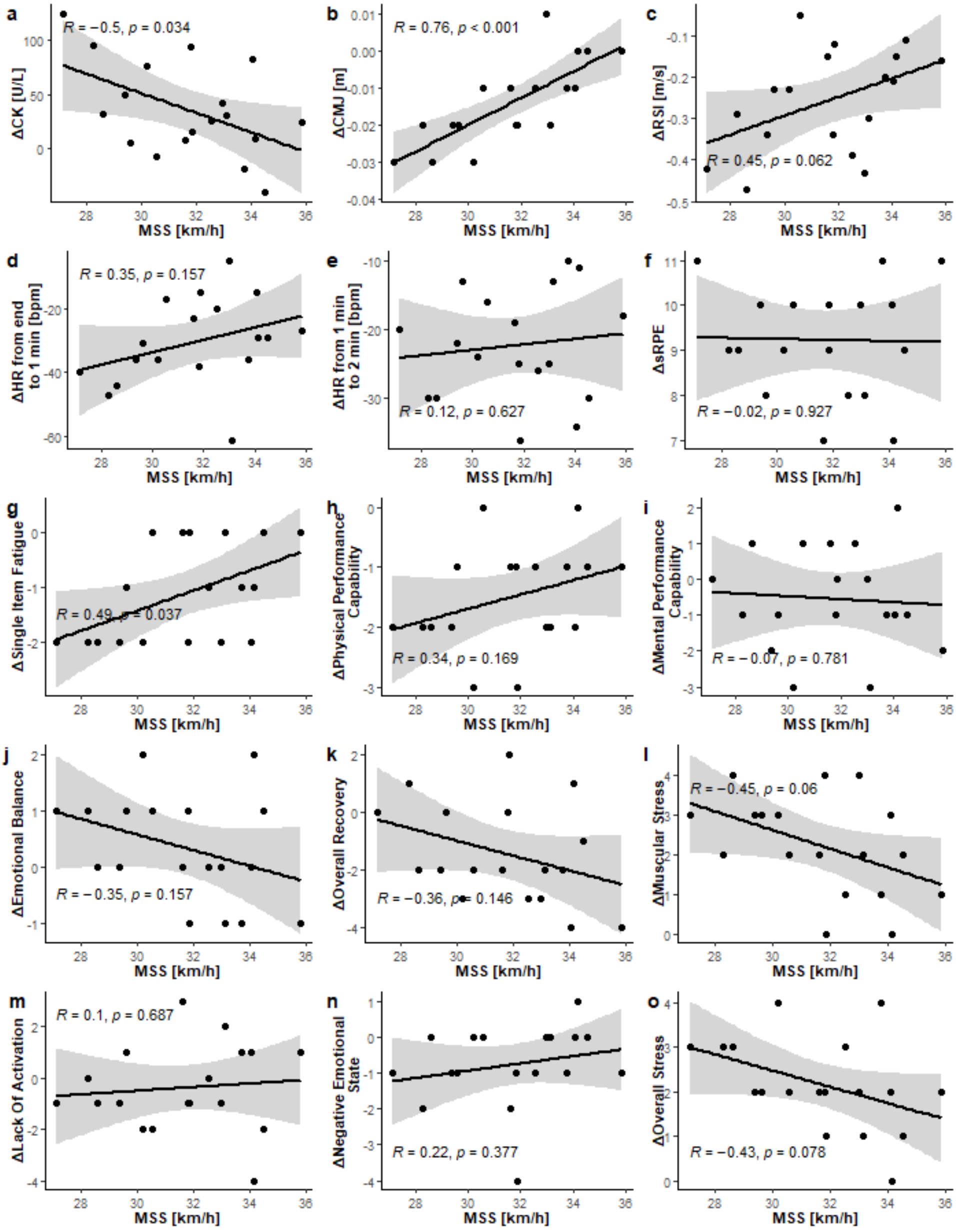

Figure 6.3: Scatterplots with regression lines and 95% confidence intervals (grey area) for MSS with the different objective and athlete-reported variables. MSS – Maximal Sprinting Speed; Δ – Delta, i.e., pre-post difference; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion; r – Pearson's r; p – significance value.

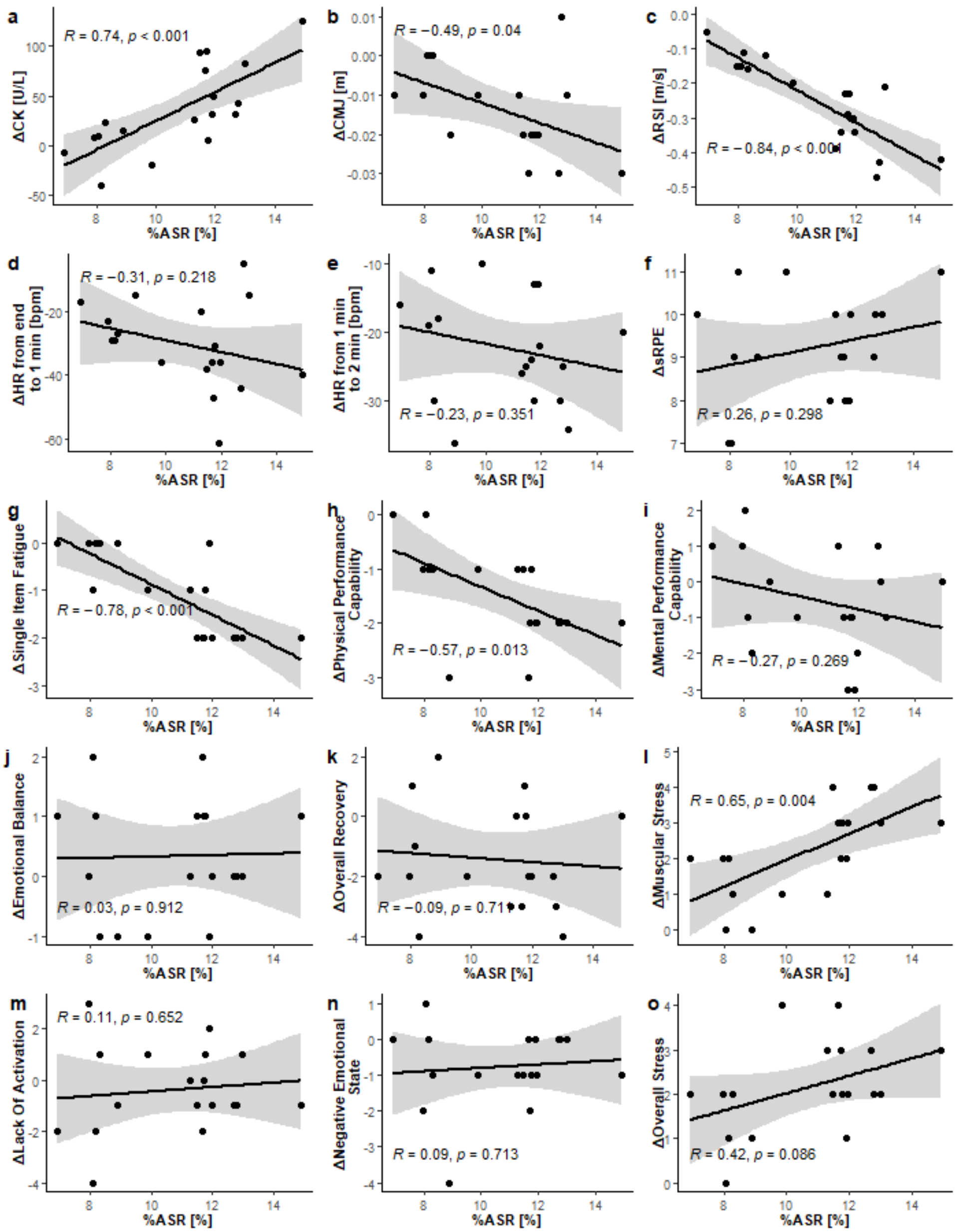

Figure 6.4: Scatterplots with regression lines and 95% confidence intervals (grey area) for %ASR with the different objective and athlete-reported variables. %ASR – percentage of anaerobic speed reserve, i.e., relative intensity of high-intensity interval training; Δ – Delta, i.e., pre-post difference; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion; r – Pearson's r; p – significance value.

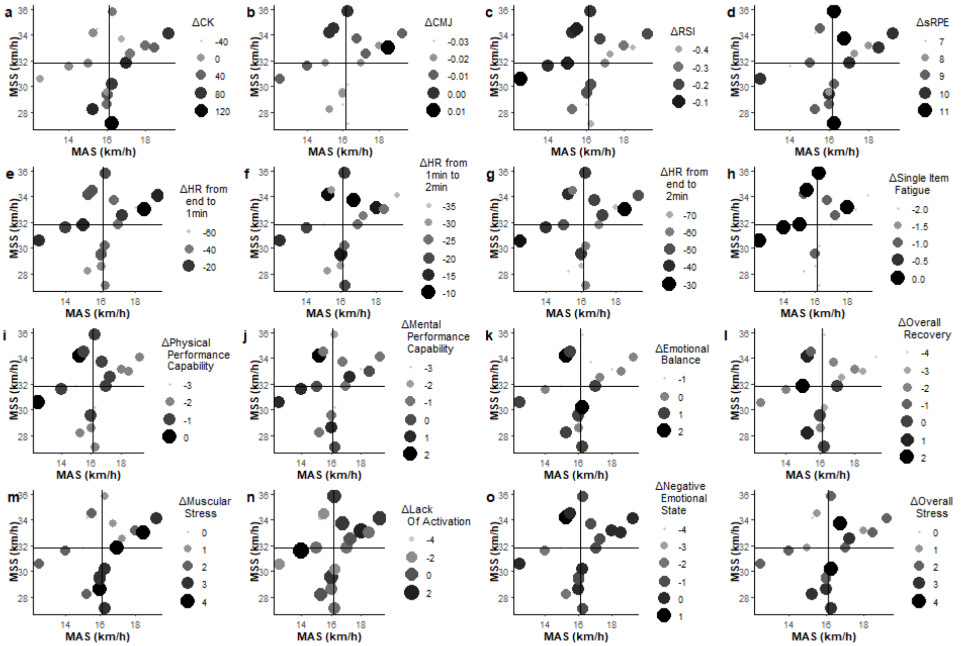

Figure 6.5: Scatterplots for the descriptive comparison of MAS and MSS with the pre/post differences of the objective and athlete-reported variables. The vertical lines represent the median of MAS and the horizontal lines the median of MSS. The size and color of the dots indicate the amount of change from pre to post of the respective response variable. MAS – Maximal Aerobic Speed; MSS – Maximal Sprinting Speed; Δ – Delta, i.e., pre/post difference; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion.

Results for Athlete-Reported Measures

The pre/post differences of the single item for fatigue, Physical Performance Capacity, Muscular Stress, and Overall Stress showed medium to very large correlations with ASR ($r \geq |0.49|$; see Figure 6.1). However, the pre/post difference of the sRPE did not show a significant relationship with ASR ($r=-0.16$; see Figure 6.1). Similarly, the pre/post differences of the single item for fatigue, Physical Performance Capacity, and Muscular Stress were significantly correlated with %ASR ($r \geq |0.57|$; see Figure 6.4). The pre/post differences of any of the athlete-reported variables did not correlate with $\dot{V}O_2max$ and MAS ($r \leq 0.45$; see Figures 6.2 and 6.3, and Supplementary Figure 6.2), while the pre/post difference of the single item for fatigue showed a positive relationship with MSS ($r=0.49$; see Figures 6.3 and 6.4)

6.1.5 Discussion

Main Findings

This study aimed to assess relationships between acute responses of physiological and athlete-reported outcome measures to short-format, MAS-based HIIT and the ASR in adolescent runners. The main findings of the present study were: (1) ASR was negatively associated with the %ASR during the HIIT, while t90%HRmax and t90%$\dot{V}O_2$max did not show any relationship with ASR; (2) ASR and %ASR showed a negative relationship with the pre/post difference of CK and a positive relationship with the pre/post difference of CMJ height and RSI; (3) the single item for perceived fatigue, Physical Performance Capacity, and Overall Recovery were positively and the Muscular Stress negatively associated with ASR and %ASR; (4) the pre/post changes did not correlate with $\dot{V}O_2$max, while only the changes in RSI correlated with MAS, and the changes in CK, CMJ height, and the single item for fatigue with MSS.

Acute Biochemical, Neuromuscular, and Cardiac Response

The MAS-based HIIT protocol used in the present study led to similar cardiorespiratory responses, i.e., t90%HRmax and t90%$\dot{V}O_2$max, during the HIIT in runners with different ASR (see also Appendix 10 Supplementary Table 1). Although the relative intensity of the HIIT as reflected by %ASR was higher for the athletes with a lower ASR, these results indicate that the cardiorespiratory load during the HIIT was comparable between the different athletes. An explanation for that could be the HIIT design being a short-format of 15 s of load following 15 s of passive rest which potentially have been too short for maximal cardiorespiratory adaptations within the 15 s of work to see potential differences between the athletes (Cipryan et al., 2017). Similar results were previously found for the comparison of endurance and sprint athletes related to the percentage of HRmax (Cipryan et al., 2017; Del Rosso et al., 2017) as well as to the percentage of $\dot{V}O_2$max achieved during HIIT (Cipryan et al., 2017). However, previous studies showed low intertrial reliability of t90%HRmax and t90%$\dot{V}O_2$max (Midgley, McNaughton, & Carroll, 2007; Ravier et al., 2017), indicating that these findings should be interpreted with caution.

Despite similar cardiorespiratory responses during a HIIT, acute biochemical and neuromuscular responses after the HIIT were likely influenced by the athletes' ASR. Athletes with a lower ASR and MSS, showed an increased CK response compared to athletes with a higher ASR and MSS. Since increased levels in CK can be a sign of exercise-induced muscle damage (Cipryan et al., 2017), our results indicate that runners with a lower ASR (and MSS) experienced remarkable muscle damage due to the short-format HIIT, while the higher ASR runners did not. According to Baird et al. (2012), the highest CK level increase occurs in the exercise with the highest intensity and shortest duration, as opposed to a longer-duration, lower-intensity session. This could be explained by the athletes with the lower ASR running the MAS-based HIIT at a higher relative intensity (%ASR) showing higher increases in CK than those with a lower ASR running the HIIT at a lower %ASR. Supported are these findings by the pre/post difference in CK being significantly correlated with %ASR. These results are supported by a higher decrease in CMJ height and RSI in the athletes with a lower ASR and MSS, pointing towards a higher acute neuromuscular load due to the HIIT compared to the runners with a higher ASR and MSS. Interestingly, these differences are mainly influenced by the athletes' ASR and MSS rather than by their $\dot{V}O_2max$ or MAS (see Appendix 16 Supplementary Figure 2 and Figures 6.2 and 6.3). Figure 5 illustrates that athletes with a lower MSS, and therefore a likely lower ASR, showed higher increases in CK and higher decreases in CMJ height and RSI from pre to post HIIT, whereas the MAS does not seem to have much influence. The differences due to an athlete's MSS and ASR in CK, CMJ height, and RSI may be due to differences in buffering or types of muscle fibers (Parkhouse et al., 1985). The athletes with a higher MSS and ASR more likely have a higher amount of fast twitch fibers than those with a lower MSS and ASR, which may increase the tolerance to metabolic acidosis (Parkhouse et al., 1985). Additionally, an impaired neuromuscular performance is strongly correlated with an decrement in muscle activation (Mendez-Villanueva et al., 2008), which is in line with lower ASR athletes running at a higher relative intensity, %ASR, and showing higher markers for muscle damage, i.e. CK, potentially leading to less muscle activation, whereby the jumping performance is impaired after the HIIT. In contrast, Buchheit, Hader, et al. (2012) found that neither $\dot{V}O_2max$ and MAS nor MSS influence the changes of CMJ and DJ height from pre to post HIIT in recreational team sports players. The discrepancies to our findings may be due to the repeated sprinting design of the HIIT inducing a different form of stress compared to the short-format HIIT in our study. Similarly to the athletes' ASR, the large correlations of the pre/post differences of CMJ height and RSI with %ASR indicate that athletes running at a higher percentage of their ASR, due to their higher MAS but lower MSS, experience a higher acute load than those running at a lower proportion of their ASR. Although, MAS-based HIIT represents one way to normalize HIIT, these results were expected as previous studies found more homogenous adaptations when the HIIT was prescribed according to ASR in comparison to MAS (Collison et al., 2022; Dai & Xie, 2023; Julio et al., 2020; Wang & Ye, 2024). Surprisingly, the HRR did not correlate with the ASR and %ASR which was not expected while the HRR is associated with blood acidosis and therefore an indirect measure of acute load (Buchheit et al., 2010). Additionally, these results are contrary to the results of Del Rosso et al. (2017) showing slower HRR kinetics in males and faster HRR kinetics in females with a high ASR compared to those with a low ASR. Also, in that study, the participants were rather heterogeneous. The load of the all-out repeated sprint exercise is not directly comparable to the short-format HIIT implemented in our study which can represent different forms of stress. In summary, our results indicate that an athlete's ASR does not affect acute cardiorespiratory responses during high-intensity exercise above MAS, while acute biochemical and neuromuscular responses and therefore the objective tolerance to HIIT differs related to an athlete's ASR and MSS due to using a lower %ASR during the exercise despite a normalized intensity based on MAS or differences in muscle fiber typology.

Acute Athlete-Reported Response

Here, the pre/post changes in sRPE did not correlate with the ASR suggesting that the perceived load during the HIIT was similar for athletes with a higher and lower ASR. Similar results were found in previous studies showing that sRPE was comparable between sprint and endurance athletes as well as between athletes with a high and low ASR after short-format HIIT (Buchheit, Hader, et al., 2012; Cipryan et al., 2017), while higher sRPE were found after long-format HIIT in endurance compared to sprint athletes (Cipryan et al., 2017). These differences between short- and long-format HIIT resulting in homogeneous and heterogeneous sRPE, respectively, might be explained by the last rest in a short-format HIIT being closer to the end of the HIIT compared to the long-format HIIT. This is also known as the peak-end rule, i.e. athletes tend to judge an experience largely based on how they felt at its most intense point (the "peak") and at its end, which might be influenced by the last break of a short-format HIIT being close to the end (Haines et al., 2020). The single item for fatigue, Physical Performance Capability, and Overall Recovery showed higher decreases and the Overall Recovery, Muscular Stress, and Overall Stress showed higher increases in athletes with a lower ASR compared to a higher ASR and %ASR (but not influenced by $\dot{V}O_2max$, MAS, or MSS; see Figures 6.2, 6.3, 6.4, and 6.5, and Appendix 16 Supplementary Figure 2). Contrary, the emotional state or motivation, as captured by variables such as Emotional Balance or Lack of Activation, did not show differences in the changes from pre to post HIIT between athletes with higher or lower ASR. An explanation could be that despite high perceived fatigue and stress, the highly-trained athletes can keep their motivation high due to their overall intrinsic motivation, goal setting, or mental resilience. Interestingly, all athlete-reported responses returned to baseline after 24 h (see Appendix 13 Supplementary Figure 1 and Appendix 15 Supplementary Table 3). Overall, it seems that different types of runners, i.e., speed-oriented (higher ASR and MSS) or endurance-oriented (higher MAS, lower ASR) runners, experience differences in acute perceived fatigue or recovery after a HIIT, while their emotional state or motivation remain similar. Additionally, their perceived fatigue or recovery returned to the initial level, indicating similar athlete-reported outcome measures related to fatigue and recovery in the longer term between athletes with different ASR types.

Limitations and Future Studies

Although our results point towards one direction, examining sex-specific differences in responses to HIIT could provide further understanding, given potential differences in ASR and acute responses (Del Rosso et al., 2017; Hallam et al., 2022; Thron, Woll, et al., 2024). Due to our rather small sample size, we did not include analyses regarding sex differences in this study; however, a sub-analysis using a student's t-test did not show any differences between sexes regarding the pre/post differences of the acute response. Further investigations should be addressed by future research. While locomotor profiling based on the SRR is additionally suggested due to potential benefits of normalization the absolute value of ASR (i.e., MAS and MSS) (Sandford, Kilding, et al., 2019), we did not look into relationships of the pre/post differences with the SRR because our data did not meet the prerequisites for calculating ratios, i.e., the regression of the numerator and denominator should intersect with the origin and the correlation of the denominator with the ratio should result in a zero correlation (Curran-Everett, 2013). Although, an inclusion criterion for the study has been that the athletes are used to HIIT, differences in the frequency or design of HIIT during their training might influence the athletes' tolerance to the short-format HIIT. Given the small number of studies determining acute athlete-reported responses to HIIT related to locomotor profiles, this research gap also needs to be filled with future studies. Although, we could already provide some insights into the behaviour of delayed athlete-reported outcome measures related to fatigue, stress, and recovery after HIIT, i.e., after 24 h, longitudinal investigations of objective and athlete-reported responses to external load are necessary to understand possible long-term differences in load mechanisms related to the locomotor profiles (Sandford et al., 2021).

6.1.6 Conclusion

In conclusion, our results underscore the importance of considering an athlete's ASR (as well as MAS and MSS) leading to different %ASR during HIIT in understanding acute responses to MAS-based HIIT by indicating higher biochemical and neuromuscular responses, and athlete-reported measures for fatigue in athletes with a lower ASR and MSS, compared to athletes with a higher ASR and MSS. However, the HIIT led to similar cardiorespiratory responses, i.e., t90%HRmax and t90%$\dot{V}O_2$max, during the HIIT in runners with different ASR. Athletes with a higher ASR might benefit from using lower proportions of their ASR during high-intensity exercise to bear higher intensities with a lower internal load than athletes with a lower ASR. These findings can provide implications for optimizing training strategies to for example avoid overload.

Practical Applications

- Coaches and practitioners should be aware that runners with a lower ASR (and MSS) show a higher acute internal (objective and athlete-reported) response to a high-intensity exercise, even when this exercise is normalized on their MAS but demanding a higher %ASR during the exercise compared to athletes with a higher ASR (and MSS). This can be of high relevance for athletes and coaches for

explaining differences in acute responses and to adjust the training cycle and stimuli to best meet an athlete's requirements.
- We recommend that a different form of short-format HIIT prescription (e.g. based on %ASR) might be more suitable for the athletes with a lower ASR and would overall lead to more homogenous responses in a group of athletes with different ASR types.
- Higher volumes and lower intensities might be best for endurance-oriented runners or lower volumes and higher intensities speed-oriented runners.

6.2 Locomotor Profile and Adaptations to Interval Training (Paper VI)

Currently under review:

Thron, M., Sondermann, Y., Ruf, L., van Hooren, B., Düking, P., Wehdemeier, L., Buday, L., Woll, A., & Altmann, S. (under review). Locomotor profile influences physiological and locomotor adaptations after six weeks of high-intensity or sprint interval training in male and female runners.

6.2.1 Abstract

Purpose. High-intensity interval training (HIIT) and sprint interval training (SIT) can improve physiological (e.g., maximal oxygen uptake ($\dot{V}O_2max$)) and locomotor (e.g., maximal aerobic speed (MAS), maximal sprinting speed (MSS)) variables. However, the influence of an athlete's locomotor profile on training adaptations to HIIT and SIT remains unclear. We aimed to 1) compare physiological and locomotor adaptations to HIIT and SIT, and 2) assess how locomotor profiles affect these adaptations. **Methods.** Twenty-seven trained male and female runners (27.7±7.5 years; n=12 women) completed six weeks of HIIT (4–6×4 min @90–95% MAS) or SIT (6–10×20 s all-out sprints), performed twice weekly. Pre- and post-tests included 40-m sprinting (MSS) and incremental treadmill tests ($\dot{V}O_2max$, MAS, lactate thresholds (e.g., v4mmol)). Anaerobic speed reserve (ASR) was calculated as MSS minus MAS and speed reserve ratio (SRR) as MSS divided by MAS. Linear mixed models and moderation analyses were performed. **Results.** Both HIIT and SIT significantly improved MAS ($p \leq 0.03$). While only SIT enhanced MSS ($p<0.01$), HIIT increased v4mmol ($p=0.01$). In both groups, speed types (i.e., higher SRR and ASR) showed greater MAS and v4mmol increases ($p \leq 0.01$) than endurance types (i.e., lower SRR and ASR). Within the SIT group, endurance types improved MSS and $\dot{V}O_2max$ more, while speed types increased $\dot{V}O_2max$ more with HIIT ($p \leq 0.03$). **Conclusion.** HIIT and SIT improve endurance outcomes in trained runners. Adaptations vary depending on locomotor profile, with speed types responding better to HIIT and endurance types benefiting more

from SIT. Accordingly, individualizing training by locomotor profile may optimize outcomes.

6.2.2 Introduction

Training for endurance performance aims to optimize key locomotor variables (e.g., maximal aerobic speed; MAS) by improving physiological outcomes (e.g., maximal oxygen uptake ($\dot{V}O_{2max}$), metabolic thresholds, running economy) (Coates et al., 2023; de Oliveira-Nunes et al., 2021). Various training intensity distributions, including polarized and pyramidal training models, aim to improve these variables. Most of these strategies incorporate training in the severe intensity domain, specifically high-intensity interval training (HIIT) above critical speed or maximal lactate steady state, to elicit efficient physiological adaptations such as increased capillary and mitochondrial density, as well as enhanced stroke volume, thereby elevating e.g. $\dot{V}O_2$max or MAS (Rosenblat et al., 2022). In the severe-intensity domain and above, high-intensity exercise can be further classified as HIIT or SIT based on the intensity and duration of the intervals, with HIIT comprising intervals >2 min at 90–120% MAS, and SIT consisting of maximal or all-out efforts <30 s at intensities >120% of MAS (Coates et al., 2023; Wen et al., 2019).

Studies investigating the adaptations resulting from HIIT and SIT, show conflicting results. Meta-analyses revealed that $\dot{V}O_2$max and MAS increased following both HIIT and SIT in untrained and trained male and female runners (Boullosa et al., 2022; de Oliveira-Nunes et al., 2021). However, subsequent studies in well-trained men and women showed considerable variability regarding endurance performance and sprinting adaptations in response to HIIT or SIT (Helgerud et al., 2023; Hov et al., 2023). While this variability may at least partly reflect measurement error and biological trial-to-trial variability, it also reflects true individual variability in response to training. This true individual variability can be driven by various factors such as morphological or genetic differences, which collectively make it difficult to apply group results to a single individual (Pickering & Kiely, 2019; Williams et al., 2017). Due to these individual responses, profiling of athletes may aid in the selection of optimal training stimuli for a specific individual (Sandford et al., 2021).

Locomotor profiles represent one way to profile athletes based on their MAS and maximal sprinting speed (MSS). Such an approach integrates maximal oxidative capacities as well as neuro-mechanical, coordinative and glycolytic capabilities. By combining these markers in the anaerobic speed reserve (ASR = MSS minus MAS) or the speed reserve ratio (SRR = MSS divided by MAS) athletes can be profiled as speed (high MSS, ASR, and SRR), hybrid (moderate MSS, MAS, ASR, and SRR), or endurance type types (high MAS but low MSS, ASR, and SRR) (Sandford et al., 2021). However, both ASR and SRR must be interpreted in the context of MAS and MSS. ASR quantifies absolute speed reserve but can be inflated by a low MAS due to an athlete being "unfit" and thus showing high ASR, whereas SRR normalizes these capacities yet incurs ratio bias. Valid interpretation requires the regression of MSS on MAS to intercept at zero, linearity between MAS and MSS, scaling of SRR should not distort statistical distribution, and no correlation between MAS and SRR to avoid distorting their relationship (Van Hooren et al., 2023). Regardless, both ASR and SRR have useful practical applications. The ASR for example is increasingly utilized for prescribing HIIT and has shown to produce more consistent chronic adaptations than MAS-based prescription (Dai & Xie, 2023). It has also been shown to lead to more uniform acute adaptations in runners when compared to MAS-prescribed HIIT (Julio et al., 2020). Moreover, ASR is a good indicator of an individual's tolerance to HIIT, with athletes having a higher ASR and MSS, i.e., speed-types, showing lower acute biochemical, neuromechanical, and athlete-reported responses to HIIT (110% MAS) than those endurance-types with a lower ASR (Thron, Ruf, et al., 2024).

Due to heterogeneous findings concerning adaptations to HIIT versus SIT, as well as the unexamined role of locomotor profiles in this context, this study aimed to (i) compare physiological and locomotor adaptations following six weeks of HIIT or SIT, and (ii) determine how baseline locomotor profiles moderate these adaptations in trained male and female runners.

6.2.3 Methods

Subjects

N=36 trained tier two female and male runners (McKay et al., 2022) initially participated in this intervention study. Sample size was determined by availability of local runners within the study's time period (July–November; convenience sample). After a drop-out of 25% due to injury (n=5), sickness (n=2), or lack of commitment (n=2), n=27 participants completed the training and were included in the analysis (women n=12). Inclusion criteria were: 18–45 years old, three to five running sessions per week, seasonal best (SB) for 5k <20:00 min for men and <27:00 for women, based on matching World Athletics scores and familiarity with interval training (27.7±7.5 years; 1.75±0.08 m; 68.08±10.88 kg; 290.4±182.3 min of training per week; 5k SB: 18:16 min for men and 24:15 min for women; see Table 6.3). This study was approved by the local ethics committee (Approval Number: 22-10) in line with the Declaration of Helsinki. The participants were informed about the procedures and possible risks and agreed to participate by signing a consent form.

Design

In this controlled trial, the participants were stratified based on their MAS and MSS (and sex-matched) to six weeks of either HIIT or SIT twice a week (see Figure 6.6). Pre-and post-testing consisted of two 40-m sprints and a cardiopulmonary exercise test (CPET) on a treadmill.

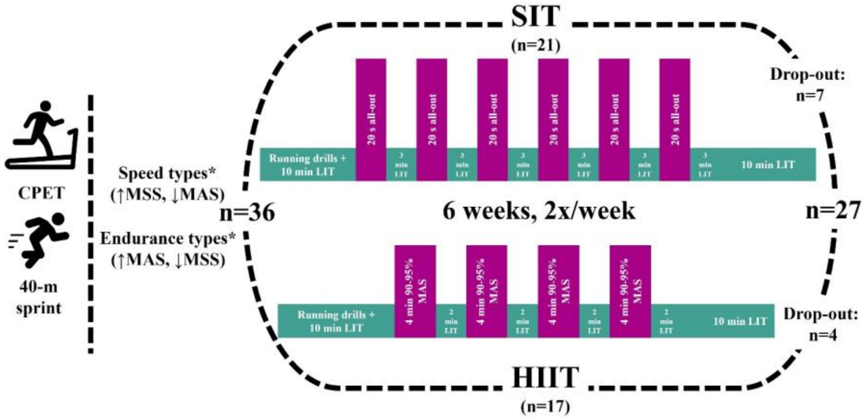

Figure 6.6: Schematic illustration of study design. SIT – sprint interval training; HIIT – high-intensity interval training; LIT – low-intensity training; MSS – maximal sprinting speed; MAS – maximal aerobic speed; * - equally assigned to both SIT and HIIT.

Methodology

Sprint Testing

The 40-m sprints were performed on an outdoor Tartan™ track. The athletes started sprinting from a standing position and the velocity was recorded with a radar gun (Stalker ATS II; 46.875 Hz; Richardson; USA) (Thron, Düking, et al., 2024), placed on a waist-high tripod two meters behind the start. The data was processed with the manufacturer's software using the dig medium filter and deleting outliers manually. The trial with the faster peak speed, i.e. MSS, was used for analysis. The time to complete the 40 m (t_{40}) was assessed using single-beam timing gates placed at waist height with error correction processing (Smartspeed Pro, Fusion Sport, Coopers Plains, Australia). The participants' starting distance from the start timing gate was set at one meter and they started self-timed.

Cardiopulmonary Exercise Testing

A cardiopulmonary (incremental) exercise test (CPET) on a motorized treadmill (PPS70 Ortho; WOODWAY GmbH; Weil am Rhein; Germany) was performed to assess lactate thresholds, running economy (RE), $\dot{V}O_2max$, and MAS. The CPET started at 6 km/h with a constant incline of 1% with increases by 2 km/h every 3 min separated by 0.5 min of rest to collect 20 µL of capillary blood from the right earlobe until a lactate concentration of

4.5 mmol/L (BIOSEN C-Line, EKF Diagnostic; Barleben; Germany) was reached. Thereafter, the speed was increased by 1 km/h every minute without interruption until participants reached subjective exhaustion (i.e., v_{peak}) under verbal encouragement. The speed at minimum lactate equivalent (vLT), LT plus 1.5 mmol/L (vIAT) (Dickhuth et al., 1999) as well as at 2, 3, and 4 mmol/L (Faude et al., 2009) were interpolated using a 3rd-degree polynomial fit. Continuous breath-by-breath gas exchange was measured using a validated CPET system (Metalyzer 3B spirometer; Cortex Biophysik GmbH; Leipzig; Germany) and a 15-second moving average filter applied prior to further analysis (Vogler et al., 2010). Gas sensors and the turbine volume transducer were calibrated using gases of known concentrations (15% O2, 5% CO2), and a 3-L syringe (Cortex Biophysik GmbH; Leipzig; Germany). $\dot{V}O_2max$ [L/min] and rel$\dot{V}O_2max$ [mL/min/kg] were assessed as the highest 30-s-interval of $\dot{V}O2$. The MAS represents the first (interpolated) velocity when reaching a $\dot{V}O2$ plateau (increase in $\dot{V}O2$ <150 ml/min in the last minute of exercise) (Thron, Düking, et al., 2024). Additionally, RE [ml/min/km] was calculated based on the $\dot{V}O2$ data of the last 30 s of a submaximal speed, i.e. 12 km/h. Steady-state $\dot{V}O2$ was confirmed visually. Physical exhaustion and thus $\dot{V}O_2max$ were checked using several parameters: The highest respiratory exchange ratio (RERend; quotient of $\dot{V}CO2$/ $\dot{V}O2$) at the end of the exercise ≥ 1.0; maximal heart rate (HRmax) as measured using a chest strap (H7 or H10; Polar Electro; Kempele; Finland; HRmax) ≥ 210-age; and rating of perceived exertion (RPE; CR10 scale) directly after test termination (RPE) ≥ 8; and at the end, and 3 min after the test, 20 µL of capillary blood was collected again to assess the maximal lactate concentration after the treadmill test (Lamax) ≥ 8 mmol/L. At least two of those criteria needed to be met (Billat & Koralsztein, 1996).

ASR was determined as the speed difference between MSS and MAS and the speed reserve ratio (SRR) was quantified as the quotient of MSS and MAS. Assumptions to calculate the ratio were verified (see Appendix 17 Supplementary Figure 1). Additionally, the aerobic speed reserve (AeSR) was calculated as the speed difference of MAS and vIAT.

Training intervention

Based on their MAS and MSS in the pre-test, the participants were stratified to six weeks of HIIT (n=13) or SIT (n=14) twice a week. Additionally, the participants conducted low-intensity training (LIT) below vLT (monitored by HR and pace). The volume of LIT was based on their weekly average training impulse (TRIMP) in two to four representative weeks before the intervention by weighting the time spent in each zone (zone 1: time <vLT×1, zone 2: between vLT and vIAT×2, zone 3: time >vIAT×3) (Düking et al., 2020; Zinner & Sperlich, 2018). The baseline TRIMP was then increased by 10% for the first two weeks and the TRIMP for the interval sessions per week was subtracted (i.e., 152 A.U.) to obtain the LIT volume. To ensure an increasing training load, the number of repetitions within the interval sessions were increased in week two and four (see Table 6.2). The participants wore either their own multisensory device for GPS tracking with a chest belt for heart rate monitoring or were equipped with a Polar Ignite watch and H10 heart rate sensor (Polar Electro; Kempele; Finland). Participants' training data (pace, HR, and RPE) were collected and monitored on a weekly basis using an online training database (Intervals.icu Ltd; London, UK).

Table 6.2: Programming of HIIT and SIT.

	HIIT	**SIT**
Warm-up	10 min <vLT + running drills	
Work intensity	90-95 % MAS	All-out sprinting
Duration of intervals	4 min	20 s
Rest intensity	<vLT	<vLT
Duration of rest	2 min	3 min
Repetitions weeks 1+2	4	6
Repetitions weeks 3+4	5	8
Repetitions weeks 5+6	6	10
Cool-down	10 min <vLT	

HIIT – high-intensity interval training; SIT – sprint interval training; vLT – velocity at minimum lactate equivalent; MAS – maximal aerobic speed.

Statistical Analysis

Statistical analyses were carried out with RStudio (R version 2024.12.0, R Foundation for Statistical Computing, Vienna, Austria) (Team, 2022). Since the data consist of a hierarchical structure, linear mixed models were applied using the *lmer* function in the *lme4* package (Bates et al., 2015) with time and group as predictors, and a random intercept per participant (outcome=group x time + (1 | ID)) with restricted maximum likelihood as estimation method. Assumptions for linear mixed models were confirmed using the *check_model* function in the *performance* package (Lüdecke et al., 2021). The *contrast* function in the *emmeans* package was used for Bonferroni post-hoc corrections to calculate within group and between group differences (i.e. pre to post differences for each group, group differences at pre and post, and differences in the changes between the two groups from pre to post) (Searle et al., 1980). Effect sizes (d) of the posthoc tests were calculated using the *eff_size* function of the *emmeans* package (based on sigma) as Cohen's d: $0.2 \leq d < 0.5$ represent small, $0.5 \leq d < 0.8$ medium, and $d \geq 0.8$ represent large effects (Cohen, 1988). To assess the moderating effects of locomotor profile upon pre to post differences, additional linear models were calculated using the *lm* function in the *stats* package (Team, 2022) (%Δoutcome=group x MAS + group x MSS; %Δoutcome=group x ASR; %Δoutcome=group x SRR). The moderator variables (i.e., MAS, MSS, ASR, SRR) were taken from the pre-testing and centered by the minimum. For all calculations, the significance level was set at α=0.05 and 95% confidence intervals (CI) were included.

6.2.4 Results

Descriptive Results

The descriptive results related to the anthropometrics, characteristics for running expertise, as well as training load are presented in Table 6.3. The training load during the intervention, i.e., the time spent in zone 1, 2, and 3 were comparable between both groups (see Table 6.3).

Results of Comparison of HIIT versus SIT

MAS ($p \leq 0.03$; $0.87 \leq d \leq 1.01$; see Appendix 18 Supplementary Table 1 and Figure 6.7, e.g. for 95% CI and mean differences) and vpeak ($p \leq 0.02$; $0.84 \leq d \leq 1.15$) both increased following HIIT and SIT. Exclusively in the HIIT group, vIAT (p=0.002; d=1.38), v3mmol (p=0.006; d=1.18) and v4mmol (p=0.007; d=1.15) increased, while ASR (p=0.01; d=-0.81) and SRR (p=0.01; d=1.08) decreased. MSS ($p<0.001$; d=2.18) and v2mmol (p=0.009; d=1.16) increased and t40 (p=0.04; d=-0.84) decreased only in the SIT group. AeSR ($p \geq 0.05$; $0.51 \leq d \leq 0.77$), rel$\dot{V}O_2max$ ($p \geq 0.45$; $0.22 \leq d \leq 0.29$), $\dot{V}O_2max$ ($p \geq 0.67$; $0.14 \leq d \leq 0.17$), vLT ($p \geq 0.08$; $0.39 \leq d \leq 0.71$), and RE ($p \geq 0.16$; $-0.57 \leq d \leq -0.55$) did not change significantly in either group.

As the sample included both male and female athletes, a sub-analysis was conducted to explore potential sex differences in adaptations to HIIT and SIT. However, adding sex as a predictor in the linear mixed models did not improve model performance for any outcome variable ($p \geq 0.19$).

Table 6.3: Anthropometrics, characteristics for running expertise, and training load for both groups.

		Overall (N = 27)	**95% CI**	**HIIT (n = 13)**	**95% CI**	**SIT (n = 14)**	**95% CI**	**p-value**
		n / N (%); Mean (SD)						
Anthropometrics	**Sex**							0.34
	female	12 / 27 (44%)	26%-40%	7 / 13 (54%)	26%-80%	5 / 14 (36%)	14%-64%	
	male	15 / 27 (56%)	36%-74%	6 / 13 (46%)	20%-74%	9 / 14 (64%)	36%-86%	
	Age [years]	27.7 (7.5)	25-31	28.9 (8.5)	24-34	26.6 (6.5)	23-30	0.44
	Height [m]	1.75 (0.08)	1.7-1.8	1.74 (0.08)	1.7-1.8	1.76 (0.08)	1.7-1.8	0.69
	Weight [kg]	68.1 (10.9)	64-72	68.2 (12.9)	60-76	68.0 (9.1)	63-73	0.97
Running Expertise	**Training [times/week]**	3.9 (1.7)	3.3-4.5	3.7 (1.5)	3.0-4.5	4.0 (1.9)	3.1-4.9	0.61
	Training [min/week]	276.1 (165.3)	220-332	262.4 (113.8)	204-321	288.4 (203.1)	191-386	0.63
	Expertise [years]	6.0 (6.2)	3.9-8.1	4.9 (5.8)	1.9-7.9	7.00 (6.5)	3.9- 10	0.31
	Seasonal best 5k [mm:ss]	20.58 (3.22)	20-22	21.25 (3.52)	19-24	20.36 (2.55)	19-22	0.51
Training load	**Zone 1 [min/week]**	356.5 (308.3)	234-478	245.7 (162.8)	147-344	459.3 (376.8)	242-677	0.07
	Zone 1 [%]	61.7 (22.5)	53-71	53.9 (19.87)	42-7	68.8 (23.2)	55-82	0.09
	Zone 2 [min/week]	133.7 (106.0)	92-176	147.3 (95.9)	89-205	121.1 (116.7)	54-188	0.53
	Zone 2 [%]	27.4 (19.4)	20-35	34.7 (21.7)	22-48	20.6 (14.70)	12-29	0.06
	Zone 3 [min/week]	55.82 (60.5)	32-80	44.6 (49.6)	15-75	66.3 (69.4)	26-106	0.36
	Zone 3[%]	10.9 (11.4)	6-15	11.3 (11.8)	4-18	10.6 (11.5)	4-17	0.88

CI – confidence interval; HIIT – high-intensity interval training; SIT – sprint interval training; SD – Standard deviation; p-value – significance level of Pearson's Chi-squared test.

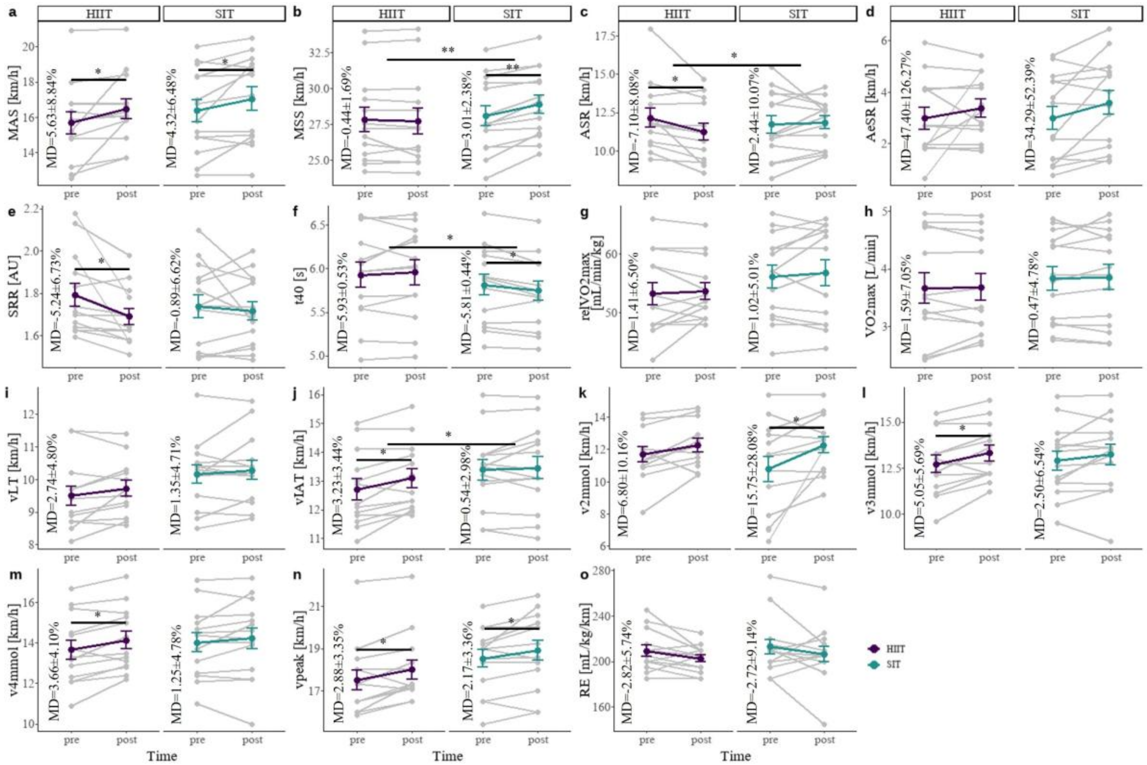

Figure 6.7: Individual trajectories with overlaid group mean and standard deviations for pre to post of HIIT and SIT groups including mean differences [%] ± standard deviation [%]. HIIT – High-intensity interval training group; SIT – Sprint interval training group; MD – Mean difference; MAS – Maximal aerobic speed; MSS – Maximal sprinting speed; ASR – Anaerobic speed reserve; AeSR – Aerobic speed reserve; SRR – Speed reserve ratio; t40 – 40-m-sprint time; VO2max – Maximal oxygen uptake; vLT – Velocity at base lactate; vIAT – Velocity at individual anaerobic lactate threshold; v2mmol/v3mmol/v4mmol – Velocity as corresponding lactate concentration; vpeak – Maximal velocity in treadmill test; RE – Running economy; * - $p<0.05$; ** $p<0.001$.

Results of Moderator Analysis

The pre to post adaptations for the locomotor variables MAS ($p<0.007$, adj. $R^2 \geq 0.30$), SRR ($p=0.003$, adj. $R^2 \geq 0.37$), and AeSR ($p=0.02$, adj. $R^2 \geq 0.27$) were influenced by the baseline MAS (see Appendix 19 Supplementary Table 2), SRR (see Appendix 19 Supplementary Table 2 and Figure 6.8), and ASR (see Appendix 22 Supplementary Table 4, and Appendix 21 Supplementary Figure 2), despite a lack of a group interaction. Higher baseline MSS and ASR led to smaller group differences concerning the change in MSS ($p=0.02$, adj. $R^2=0.52$; $p=0.03$, adj. $R^2=0.49$, respectively). Similarly, higher baseline MSS resulted in a smaller group difference for the change in ASR ($p=0.008$, adj. $R^2=0.50$).

Regarding physiological adaptations, athletes' baseline SRR moderated the influence of both groups on adaptations of rel$\dot{V}O_2$max ($p=0.03$, adj. $R^2=0.09$; see Appendix 20 Supplementary Table 3 and Figure 6.9). Additionally, the changes of v3mmol and v4mmol are influenced by baseline SRR ($p=0.03$, adj. $R^2=0.15$; $p=0.045$, adj. $R^2=0.13$, respectively), without group interaction.

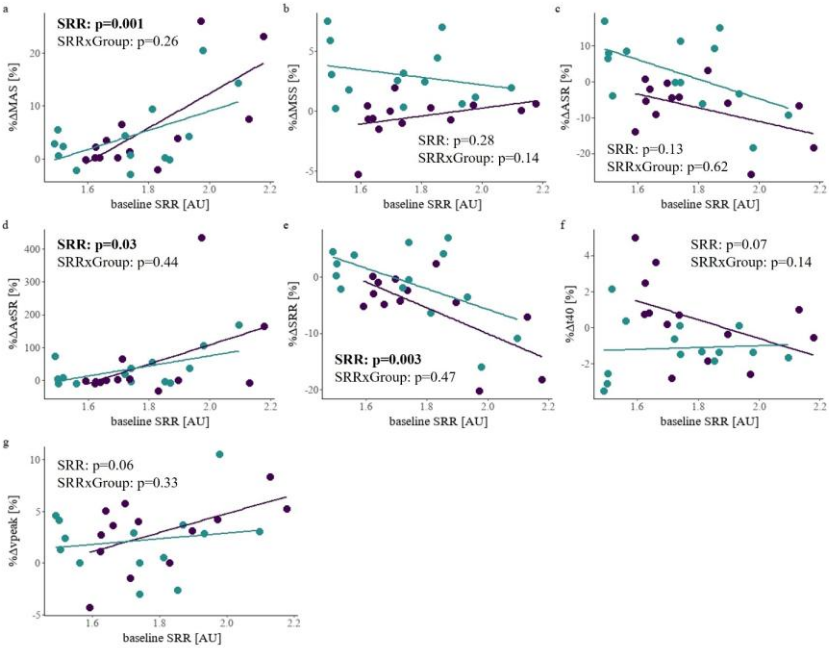

Figure 6.8: Interaction plots between baseline SRR and percentage changes of locomotor variables with main and interaction effects of moderator analyses. HIIT – High-intensity interval training group; SIT – Sprint interval training group; %Δ – Percentage difference from pre to post; MAS – Maximal aerobic speed; MSS – Maximal sprinting speed; ASR – Anaerobic speed reserve; AeSR – Aerobic speed reserve; SRR – Speed reserve ratio; t40 – 40-m-sprint time; vpeak – Maximal velocity in treadmill test; p - significance value (bold values are $p<0.05$).

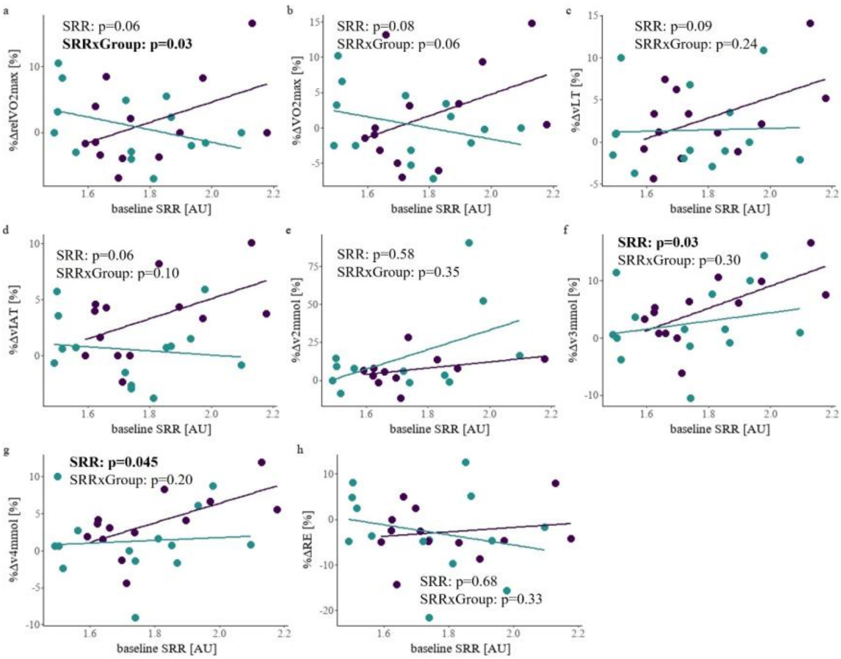

Figure 6.9: Interaction plots between baseline SRR and percentage changes of physiological variables with main and interaction effects of moderator analyses. HIIT – High-intensity interval training group; SIT – Sprint interval training group; %Δ – Percentage difference from pre to post; SRR – Speed reserve ratio; $\dot{V}O_2max$ – Maximal oxygen uptake; vLT – Velocity at minimum lactate equivalent; vIAT – Velocity at individual anaerobic lactate threshold; v2mmol/v3mmol/v4mmol – Velocity as corresponding lactate concentration; RE – Running economy; p - significance value (bold values are $p<0.05$).

6.2.5 Discussion

Main Findings

This study aimed to (i) compare physiological and locomotor adaptations to six weeks of HIIT or SIT, and (ii) determine how baseline locomotor profiles moderate these adaptations in trained male and female runners.

The main findings of the present study were:

(1) MAS increased in both groups. vIAT and v4mmol increased, and ASR and SRR decreased only in the HIIT group, while MSS and t40 only improved following SIT;
(2) (rel)$\dot{V}O_2max$ and RE did not change in either group;

(3) Athletes with a higher SRR and ASR but lower MAS, i.e., speed-type athletes, showed larger increases in MAS, v3mmol, and v4mmol than endurance-type athletes independent of the group;
(4) Speed-type athletes in the HIIT group showed higher increases in rel$\dot{V}O_2max$ and in the SIT group lower increases in rel$\dot{V}O_2max$ and MSS than endurance-type athletes.

Comparison of HIIT versus SIT

The results of the present study show that six weeks of HIIT or SIT are effective to improve MAS but not $\dot{V}O_2max$ in a group of trained male and female runners. These findings contrast previous studies that found both HIIT and SIT to effectively improved $\dot{V}O_2max$ (de Oliveira-Nunes et al., 2021). However, a tendency of less improvement of $\dot{V}O_2max$ with shorter interval duration and longer rest duration has previously been identified (Rosenblat et al., 2022). This might be due to shorter time spent at intensities above 90% of $\dot{V}O_2max$, which in turn is an important aspect to increase $\dot{V}O_{2max}$ (de Oliveira-Nunes et al., 2021). Differences in interval protocols could explain the differences of our results. Furthermore, an improved RE can lead to improved performance without a change in $\dot{V}O_2max$ (Billat et al., 1999). Therefore, the improved MAS may reflect an improved RE although $\dot{V}O_2max$ was not enhanced.

RE did not change significantly despite medium effect sizes ($d \geq |0.55|$), indicating a tendency toward improved RE following both HIIT and SIT. Given that longer work-bouts more effectively enhance RE, the 4-min HIIT intervals and in particular the SIT bouts in our study may have been too short or the speed too high to reach those adaptations improving RE on a group level, potentially due to a loss in running form at very high speed for some participants (Barnes & Kilding, 2015b). Additionally, the importance of high (life time) training volume has been identified for improving RE, which might have been too low in this 6-weeks training intervention (Barnes & Kilding, 2015b).

The group differences that showed HIIT to be more effective at improving performances at lactate thresholds (i.e., vIAT and v4mmol), and SIT at improving sprint performance (i.e. MSS and t40) are in line with the literature (Helgerud et al., 2023; Hov et al., 2023). These differences might be explained by HIIT improving acid-base transport protein abundance and muscle buffer capacity which in turn positively influence lactate kinetics (McGinley & Bishop, 2016), whereas SIT primarily affects neuromuscular and anaerobic capabilities (Helgerud et al., 2023).

Locomotor types proved mutable, i.e., SIT elicited concurrent MAS and MSS gains without altering ASR or SRR, whereas HIIT's isolated MAS enhancement reduced both reserves (see Figure 6.7). Similarly, Dai and Xie (2023) also reported a decrease of ASR following six weeks of HIIT (using a different protocol) in soccer players. Collectively, these results indicate that the locomotor profile can be altered to some extent using a specific training stimulus.

Influence of Locomotor Profile

Both formats of interval training were more effective at improving aerobic endurance performance (MAS and lactate thresholds) in speed-type athletes than in endurance-type athletes. Speed-types' larger MAS gains likely stem from their lower baseline MAS, and therefore larger adaption potential. Contrary to the assumption that endurance performance in speed-types might be best enhanced using repeated sprinting (Sandford et al., 2021), the present findings indicate that speed types can also benefit from long-format HIIT sessions. However, their fiber-type composition may reduce high-volume tolerance, warranting future longitudinal load-and-fatigue monitoring (Bellinger et al., 2020; Sandford et al., 2021). On the other hand, both training formats might not have been optimal for improving MAS and lactate thresholds in endurance types. Potentially a larger increase in total volume and in the slow and continuous work (<vLT) might be more beneficial than increasing HIIT volume for endurance types (Sandford et al., 2021; Seiler, 2010).

Interestingly, physiological adaptations in rel$\dot{V}O_2max$ were higher for speed-types in the HIIT group and for endurance-types in the SIT group (Figure 6.9), despite no differences between groups. Therefore, individual profiles can influence changes in rel$\dot{V}O_2max$ depending on the interval format, thereby masking group effects. Selected genes and muscle fiber typology have been shown to be very strong predictors of responsiveness to training (Meyler et al., 2021; Williams et al., 2017), influencing different adaptations between speed- and endurance types. Additionally, HIIT has shown to elicit higher $\dot{V}O_2max$ by means of central adaptations such as cardiac function, while SIT has also been associated with improved peripheral factors such as angiogenesis (Rosenblat et al., 2022). This leads to the hypothesis that speed-types might have been limited more peripherally at baseline and thus showcased better adaptations following HIIT due to greater potential for adaptations of central factors such as cardiac output. On the other hand, endurance-types might already exhibit high cardiac output and therefore benefit more from enhanced peripheral factors caused by SIT. To confirm this hypothesis, future studies need to explore in more detail whether the profile-specific adaptations are mediated by peripheral and central factors.

Furthermore, the changes in MSS and ASR are mainly influenced by the athletes' baseline MSS (see Appendix 19 Supplementary Table 2). Athletes in the SIT group with a lower baseline MSS and baseline MAS within their group (but higher ASR) showed higher increases in MSS and therefore decreases in ASR than those with a higher baseline MSS. In contrast, baseline MSS (or MAS, SRR) did not influence adaptations in the HIIT group. These results indicate that changes in MSS are not predominantly influenced by a locomotor profile but rather by its baseline level, i.e. larger improvements in slower athletes. Additionally, speed-type athletes in both groups show larger decreases in their SRR, pointing toward a change in their locomotor profile from speed to hybrid types, while the SRR of endurance-type athletes remained more stable. Since a significant change in muscle fiber typology following six weeks of training is unlikely, the locomotor profile of this sample, i.e. trained runners, could be linked to exercise habits and conditioning and less to muscle fiber typology (Dai & Xie, 2023). Therefore, less trained athletes benefit from both SIT and HIIT for increasing MAS and hence a decrease in SRR.

Practical Applications

Our findings indicate that SIT might be a time-efficient method to increase MAS and MSS in trained male and female runners. However, it is noteworthy to mention that the drop-out rate in the SIT group due to injuries (SIT: 21.1%, HIIT: 5.9%) has been descriptively higher than in the HIIT group. While the perceived effort (average RPE for all sessions) was comparable between groups (SIT: 7.5±1.2, HIIT: 7.9±0.8), the mechanical load of six weeks of SIT may have exceeded the tissue tolerance in this cohort, despite prior HIIT experience.

Notably, speed-type athletes responded well to HIIT, indicating that longer intervals can benefit this group beyond sprint-specific work. Conversely, endurance-type runners may require higher total volumes or additional low-intensity training to elicit meaningful improvements in MAS and lactate thresholds, while SIT may serve as a stimulus enhancing peripheral factors and thus $\dot{V}O_{2max}$. The marked interindividual variability in locomotor profiles and responses to training underscores the need for individualized training prescription. Changes in ASR and SRR demonstrate that locomotor profiles are adaptable, supporting the use of targeted stimuli to shape an athlete’s speed–endurance characteristics in line with race demands or seasonal objectives. Interval training could therefore be prescribed with consideration of locomotor typology, baseline characteristics, and sport-specific requirements.

Nevertheless, these recommendations should be considered with respect to the study’s limitations. Despite the use of HR and pace monitoring, along with weekly feedback, prescribed intensities were difficult to sustain, especially in the SIT group, where fatigue and motivation varied. The implementation of advanced monitoring strategies, such as real-time (wearable-based) feedback, may enhance adherence and improve intensity consistency in future studies. Furthermore, athletes in both groups conducted the six weeks of training with the same pyramidal intensity distribution (see Table 6.3), because the aim was to compare HIIT and SIT adaptations and the influence of their locomotor profile. Different training intensity distributions have shown to be successful in reaching optimal and desired adaptations (Zinner & Sperlich, 2018) but the influence of the locomotor profile on individual adaptations to different intensity distributions requires more investigation. Additionally, physiological and athlete-reported load to different forms of training with respect to the locomotor profile should be addressed in future research (Sandford et al., 2021; Thron, Ruf, et al., 2024).

6.2.6 Conclusion

In conclusion, this study demonstrates that six weeks of HIIT or SIT can improve MAS in trained runners, without improvements in $\dot{V}O_2max$ on a group level. There was however large inter-individual variability with speed-type runners showing greater improvements in MAS and lactate thresholds in both groups and in $\dot{V}O_2max$ following HIIT, indicating a higher aerobic response to longer, high-intensity intervals. In contrast, endurance-type athletes responded more favorably to SIT in terms of $\dot{V}O_2max$ and MSS, suggesting that the short, high-intensity efforts may serve as a potent stimulus for neuromuscular and metabolic adaptation. These differences imply that an athlete's locomotor profile influences their responsiveness to different interval formats. Understanding these differential responses is crucial for optimizing training strategies and highlights the need to consider individual profiles when selecting training stimuli in performance development.

7 General Discussion

In endurance sports, testing of several determinants of endurance performance is a crucial part in evaluating and adapting training processes within a training cycle. Traditional models rely mainly on $\dot{V}O_2max$, performance $\dot{V}O_2$, and RE (Joyner, 1991) for estimating running performance (see Chapter 2.2.1). More recent research highlights the importance of anaerobic or neuromuscular contributions to endurance performance (Joyner & Coyle, 2008; Paavolainen, Häkkinen, et al., 1999). In this regard, profiling of athletes based on physiological or locomotor marker aims to provide a framework for characterizing athletes based on several capabilities: Physiological profiling, through $\dot{V}O_2max$ and $\dot{c}Lamax$, offers valuable information about an athlete's aerobic capacity and anaerobic power. In contrast, locomotor profiling, derived from the ASR and its subcomponents, provides a complementary perspective by including metabolic, neuromuscular, and mechanical-coordinative variables (see Chapter 2.3.2). While both approaches attract considerable interest in research and practice, several research gaps regarding associations between approaches, methodological aspects of testing, as well as practical application in training remained unsolved (see Chapter 2.3.3). Hence, the purpose of this thesis considered:

A. To investigate the value and relationship between physiological and locomotor profiling across running disciplines.
B. To evaluate and systematically review the validity and reliability of tests to assess MAS and MSS in running-based sports.
C. To examine the role of locomotor profiles in explaining acute responses and chronic adaptations to different HIIT formats.

The three aims of this thesis were pursued through a systematic review (Paper III) and five original studies (Papers I+II, IV–VI). The following subchapters synthesizes the main findings and situates them within both the specific scope of the research and the broader scientific context (Chapter 7.1). In addition, the limitations of the presented studies will be addressed as well as directions for future research (Chapter 7.2) and practical implications for researchers and practitioners in the field of running-based sports (Chapter 7.3).

7.1 Main Findings

7.1.1 The Value of Profiling for Differentiating between Runners (Paper I)

Endurance performance in running-based sports is shaped by metabolic, mechanical, and neuromuscular factors (Hallam et al., 2022; Jones, 2023). Rather than relying on single markers, profiling approaches that integrate multiple characteristics may enhance training individualization, monitoring of adaptations, and talent identification (Weakley et al., 2024). Physiological profiling, using $\dot{V}O_2max$ and ċLamax, captures the interaction of oxidative and glycolytic energy pathways (Wackerhage et al., 2022), while locomotor profiling, based on MAS and MSS, combines physiological, mechanical, and neuromuscular markers (Sandford & Stellingwerff, 2019). Although both approaches seem to be promising in evaluating running performance (Hallam et al., 2022; Lundby et al., 2017; Quittmann et al., 2023), their interrelationship remained unclear, particularly across running disciplines. To address this gap, the first aim of this thesis was to compare physiological and locomotor profiles of adolescent and young adult sprinters, 400-m runners, and middle-distance runners which was addressed by Paper I (see Chapter 4).

The main findings of Paper I were:

- Profiles differ by discipline: 400-m and middle-distance runners displayed higher MAS and $\dot{V}O_2max$ than sprinters, whereas sprinters and 400-m runners showed higher MSS and ċLamax than middle-distance runners.
- Strong correlations were observed within aerobic parameters (MAS and $\dot{V}O_2max$) and within anaerobic-mechanical parameters (MSS and ċLamax) of both approaches, whereas no association emerged between aerobic and anaerobic measures.

These findings show clear differences in physiological profiles (ċLamax, $\dot{V}O_2max$) between different running disciplines. Specifically, 400-m runners displayed anaerobic power (ċLamax) similar to sprinters but aerobic capacity ($\dot{V}O_2max$) comparable to middle-distance runners, consistent with evidence that 400-m performance relies equally on aerobic and anaerobic energy supply (Nevill et al., 2008; Quittmann et al., 2020). Within the 400-m runners, higher world athletics (WA) scores were associated with higher ċLamax but not $\dot{V}O_2max$, suggesting that anaerobic power may be more critical for 400-m performance. Locomotor profiles also varied across disciplines, depending on sex. Female 400-m runners showed MAS values similar to female middle-distance runners, while male 400-m runners had lower MAS than middle-distance runners, in line with earlier findings (Hallam et al., 2022; Sandford, Allen, et al., 2019). Moreover, mechanical and kinematic factors, such as stride characteristics, likely contribute to differences in MSS between disciplines (Cunningham et al., 2013). Following Sandford et al. (2021), sprinters in this study align with a speed profile, middle-distance runners with an endurance profile, and 400-m runners spanning endurance, hybrid, and speed profiles. Moreover, correlational analyses revealed that aerobic parameters (MAS, $\dot{V}O_2max$) and anaerobic-mechanical parameters (MSS, ċLamax) are positively related within their domains but independent of each other. ASR and SRR, integrating both MAS and MSS, correlated positively with anaerobic-mechanical and negatively with aerobic markers. Taken together with the observed between-discipline differences, these findings suggest that physiological and locomotor profiles are interrelated and that both approaches can distinguish between athlete subgroups.

However, it is noteworthy to mention that several concerns were recently raised regarding ċLamax, challenging the determination of maximal glycolytic rate from blood lactate accumulation. Specifically, (1) glycolytic flux is unlikely to reach its true maximum during an all-out exercise test, (2) peak flux is only sustained for a very short duration, (3) there is no definitive criterion to confirm attainment of ċLamax, (4) no correction is made for lactate clearance occurring between exercise termination and blood sampling, (5) oxidative ATP resynthesis is not accounted for, and (6) the alactic time correction itself is prone to error (Wackerhage et al., 2025). Together with the methodological effort involved in assessing ċLamax and high correlations with MSS detected in Paper I, it can be assumed that sprint performance itself, i.e. MSS, represents a sufficient marker for profiling by determining athletes' anaerobic power but also neuromuscular-mechanical capabilities. However, locomotor profiling using MSS together with MAS to calculate ASR or SRR require careful interpretation as well. While ASR captures the absolute reserve between maximal sprinting and aerobic speeds, it can appear artificially high if MAS is low, for example in less aerobically trained athletes. On the other hand, SRR adjusts for this by expressing the reserve as a ratio, yet such normalization introduces potential ratio bias. Meaningful use of these indices assumes that MSS scales linearly with MAS, that the regression intercepts at zero, that SRR scaling does not distort statistical distributions, and that MAS and SRR remain uncorrelated to avoid confounding their relationship (Van Hooren et al., 2023). When these pitfalls are taken into account and the absolute values of MAS and MSS are always considered, locomotor profiling can allow more robust subgroup differentiation than physiological profiling (Sandford et al., 2021).

Based on these considerations, the following studies focused on locomotor profiling rather than physiological profiling regarding its valid and reliable assessment in running-based sports (Chapter 7.1.2) as well as the application in explaining acute responses and chronic adaptations to different formats of endurance training (Chapter 7.1.3).

7.1.2 Methods to Assess the Locomotor Profile (Anaerobic Speed Reserve) (Paper II – IV)

As accurate assessment of MAS and MSS is critical for both athlete profiling and ASR-based training prescription, care must be taken to minimize measurement error from technological, biological, or intraindividual sources (Simperingham et al., 2016). Additionally, exploring submaximal predictors of v_{peak} as an estimation for maximal aerobic power (e.g., MAS) may enhance performance monitoring during high training loads (Buchheit, Simpson, et al., 2012). Therefore, Papers II–IV aimed to evaluate and systematically review validity and reliability of methods to assess MAS and MSS as well as the potential of submaximal predictors of v_{peak}.

All three articles address the different methods for assessing the locomotor profile, and their key findings can be summarized as follows:

- Different definitions and protocols to assess MAS via $\dot{V}O_2$-kinetics of CPET yield different results (Paper II + III)
- Most field tests overestimate CPET-based MAS (Paper II + III)
- Age, sex, and vL4 adequately predict v_{peak} (Paper IV)
- MSS can be accurately assessed via radar, timing gates, or video analysis (Paper III)

Different definitions and protocols to assess MAS via $\dot{V}O_2$-kinetics of CPET yield different results

Originally, MAS was defined by Di Prampero et al. (1986) as the minimum running velocity at which $\dot{V}O_2$ ceases to increase despite higher workloads, marking the onset of a VO_2 plateau (i.e., $MAS_{Plateau}$). However, different definitions and treadmill protocols to assess MAS via CPET and therefore substantial variation exists, leading to differing results.

The systematic review (Paper III) summarizes that protocol design significantly affects MAS outcomes. For example, when increments and stage durations were proportional (e.g., 1 km/h every 2 min vs. 0.5 km/h every 1 min), results for MAS were similar (Billat et al., 1996), but longer stage durations within the same increment reduced MAS by about 2 km/h (Riboli et al., 2017; Riboli et al., 2022). Square-wave protocols with rest intervals tend to yield higher MAS values than continuous incremental protocols (Riboli et al., 2017; Riboli et al., 2022). To ensure valid assessment, protocols should allow subjects to actually reach $\dot{V}O_2max$, verified by a $\dot{V}O_2$ plateau or secondary criteria such as blood lactate, respiratory exchange ratio, HR, or RPE (Midgley, McNaughton, Polman, et al., 2007). In this regard, Paper III summarizes that continuous incremental protocols lasting 8–16 minutes with 1 km/h increments are often recommended, with stage durations adapted to athletes' background: longer stages (2–3 min) for endurance-trained athletes, and shorter stages (1 min) for athletes accustomed to high-intensity efforts (e.g., team sport athletes) to avoid neuromuscular exhaustion (Midgley, McNaughton, Polman, et al., 2007; Niemeyer et al., 2021).

Beyond protocol variation, the choice of MAS definition has important consequences. Paper II and Paper III show systematic differences between two common definitions of MAS, i.e., the speed at the onset of the $\dot{V}O_2$ plateau ($MAS_{Plateau}$) and the speed at the 30-s interval of $\dot{V}O_2max$ (MAS_{30s}). Because $\dot{V}O_2max$ in healthy subjects is usually reached before exhaustion and a $\dot{V}O_2$ plateau must persist for at least one minute (Meyer, Scharhag, et al., 2005), MAS_{30s} typically occurs at a higher speed than $MAS_{Plateau}$. Paper II showed that on average, MAS_{30s} exceeds $MAS_{Plateau}$ by around 1 km/h supported by greater anaerobic contribution (Buchheit, 2010). Moreover, while $MAS_{Plateau}$ reflects the maximal speed achieved with predominantly aerobic energy supply, MAS_{30s} represents intensities with a substantially higher anaerobic demand. The strong correlation but consistent overestimation of MAS when using MAS_{30s} highlights the practical importance of distinguishing between these definitions (Berthoin et al., 1996; Da Silva & Machado, 2015). This is particularly important for training applications, especially when prescribing HIIT based on MAS or ASR. Using MAS definitions beyond the onset of the $\dot{V}O_2$ plateau., e.g., MAS_{30s}, risks prescribing intensities that exceed "true" MAS. This may lead to unintended adaptations or even overtraining. Therefore, when prescribing training intensities, $MAS_{Plateau}$ should be used to ensure accurate application of common methods (e.g., 110% MAS or 130% ASR). If alternative measures such as MAS_{30s} are used, the overestimation of MAS must be considered, and training loads should be adjusted accordingly (e.g., 105% MAS_{30s}). Furthermore, when MAS is applied to monitor performance changes, it is essential to consistently use the same testing protocol and definition over time to exclude performance changes due to measurement errors.

Most field tests overestimate CPET-based MAS

The systematic review (Paper III) shows that several field tests (i.e., incremental continuous, incremental shuttle runs, or time trials) have been developed to estimate MAS as practical alternatives to CPET. These tests are widely used because they require less equipment, time, and expertise than CPET. When identical protocols were applied in CPET and the incremental continuous field tests such as the Université de Montréal Track Test (UMTT), validity was reported heterogenous (Cappa et al., 2014; Lopes et al., 2015; Pallarés et al., 2019), while reliability was reported as good (Léger & Boucher, 1980). Importantly, Paper II revealed that the final speed of UMTT was on average 1.61 km/h higher than $MAS_{Plateau}$ determined by CPET. Since the final speed of UMTT as an incremental running test is similar to v_{peak}, and v_{peak} is typically around 1 km/h higher than MAS (Buchheit, 2008), it is not surprising that the UMTT overestimates MAS as well. These findings suggest that using this the UMTT for training prescription of common HIIT protocols may lead to excessive intensities and risk of maladaptation or overtraining.

Time trials (TT) are another common method to assess MAS, favored for their simplicity in both research and applied contexts (Bellenger et al., 2015) and are investigated in Papers II and III as well. The average velocity in 5-min time trials showed reasonable agreement with CPET or UMTT results in various populations (Berthon, Dabonneville, et al., 1997; Berthon, Fellmann, et al., 1997; Darendeli et al., 2021). However, set-distance TT (1,200–2,200 m) generally overestimated MAS when compared to CPET, depending on sex, type of sport, or fitness level (Foster et al., 2022; Lacour et al., 1991; Lorenzen et al., 2009; Sandford, Rogers, et al., 2019). Although a predictive equation have been suggested to estimate MAS from TT performance (Bellenger et al., 2015), Paper II did not confirm its validity. Potentially due to the equation outcome being assessed via the UMTT an not CPET-derived MAS and differences in fitness levels between samples. Moreover, Paper II showed that for some players the average speed of the 1,500-m TT is relatively close to MAS and, while the dispersion was very high in general. Together with findings from Paper III, those results indicate that the distance should be selected according to the athletes' background, with shorter distances (1,200–1,400 m) being more suitable for athletes with lower aerobic capacity or more anaerobically determined sports such as some team sports, and longer distances (1,500–2,000 m) providing closer estimates for endurance-trained athletes.

As presented in the systematic review (*Paper III*), shuttle runs also aim to assess MAS while involving frequent changes of direction and are often used in team sports, due to their similarity with the nature of most team sports and easy applicability. Most studies using CPET as the criterion found that the final speed of shuttle runs (e.g., 30-15 intermittent fitness test or Yo-Yo intermittent running test) is not a valid estimate of MAS (Barbero-Alvarez et al., 2015; Čović et al., 2016), likely due to the higher anaerobic contribution and energetic cost of direction changes (Buchheit, 2010). Although some shuttle tests have demonstrated good reliability (Čović et al., 2016; Schnitzler et al., 2010), their tendency to overestimate MAS limits their utility for precise training prescription.

Together, the findings of Paper II and the systematic review in Paper III emphasize that while field tests offer practical alternatives to laboratory-based CPET, their validity and accuracy depend on protocol design, the definition of MAS applied, and the athlete population under study. Careful consideration is therefore required when using field-based estimates of MAS for training prescription or comparison of athletes. Similarly to the different definitions of MAS as discussed above, estimates derived from field tests must be interpreted with caution. Deviations from true MAS should be accounted for, and training loads adjusted accordingly (e.g., 105% of the final velocity in the UMTT). For monitoring performance changes, reliability of testing methods gets more important. All of the mentioned field-tests showed good reliability results, thus to monitor performance changes with field tests, it is crucial to apply the same testing method consistently.

Age, sex, and vL4 adequately predict v_{peak}

Besides MAS, peak incremental running test speed (v_{peak}) can be assessed on a treadmill or in the field and is a widely recognized indicator of aerobic fitness and endurance performance (Stratton et al., 2009). While v_{peak} overestimates true MAS (Berthoin et al., 1996; Da Silva & Machado, 2015), it is still a valuable measure for assessing endurance performance without the use of breathing gas data and can be used for training prescription when methods are altered (i.e., 105% v_{peak} for HIIT). While submaximal prediction of v_{peak} could simplify training processes by preventing physical exhaustion, *Paper IV* demonstrates that fixed lactate thresholds, particularly vL4, together with age and sex, are strong predictors of v_{peak} across different test modes (i.e., treadmill or field). Incorporating fractional utilization of HRmax at a submaximal speed further improved predictive accuracy. The strong relationship between vL4 and v_{peak} is consistent with earlier findings (Alves Pasqua et al., 2016; Peyré-Tartaruga et al., 2024). Physiologically, greater mitochondrial density and enzymatic activity may reduce metabolic acidosis, enabling sustained exercise at higher speeds without impairing oxidative metabolism, thereby supporting higher v_{peak} (Peyré-Tartaruga et al., 2024). Age- and sex-related effects also align with established differences in oxidative capacity, which declines with age and tends to be lower in women (Peyré-Tartaruga et al., 2024). Together, vL4, age, and sex explained 80% of the variance in v_{peak}, with a cross-validated prediction error of 0.64 km/h. Including fractional utilization of HRmax increased the explained variance to 83% and lowered the prediction error to 0.60 km/h. This finding reflects the physiological link between lower fractional utilization of HRmax at submaximal intensities and superior aerobic performance (Buchheit, Simpson, et al., 2012), which translates into a higher v_{peak}. Overall, Paper IV identified practically useful, submaximal predictors of v_{peak} and provided regression equations as well as an online calculator for an easily accessible calculation.

MSS can be accurately assessed via radar, timing gates, or video analysis

Regarding the assessment of MSS, radar and laser technology are considered the gold standard among the available methods, providing accurate speed profiles during linear sprinting of 30–70 m (Beato et al., 2018; Romero-Franco et al., 2017). However, radar and laser technology is associated with high costs, hence several different methods are recently used to measure MSS. As presented in Paper III, those methods most commonly include timing gates, GPS or LPS, smartphone-based video analysis, or also treadmill sprinting. Besides reliability, validity of those methods is discussed in the following when compared to the gold standard, laser or radar, if not stated otherwise (i.e. criterion validity).

Timing gates are widely used due to their practicality in applied settings in track and field and also in team sports. Validity studies show that average speed from 5-m as well as 10-m splits provides sufficient estimates of MSS compared to radar or motorized encoders (Fornasier-Santos et al., 2022; Roe et al., 2017; Zabaloy, Freitas, et al., 2021), while sprint distances between 20 and 40 m are adequate for team-sport athletes to reach MSS (Ferro et al., 2014; Vescovi, 2012; Young et al., 2008; Zabaloy, Giráldez, et al., 2021). In contrast, track and field sprinters may require 40–70 m to achieve MSS due to their differences in acceleration patterns (Healy et al., 2022; Majumdar & Robergs, 2011). Intraday reliability of timing gates is good (Fornasier-Santos et al., 2022; Helland et al., 2019; Zabaloy, Freitas, et al., 2021; Zabaloy, Giráldez, et al., 2021), and although interday reliability has not been directly examined for MSS, studies on other sprint metrics such as acceleration suggest that it is acceptable (Altmann et al., 2019; Haugen et al., 2012).

In addition, GPS and LPS systems have gained popularity due to their ability to capture speed data in both training and match contexts, in which the data is captured for example for match analysis (Massard et al., 2018). However, studies on validity for MSS assessment is reported heterogeneously and mainly conducted with soccer players. While several studies reported acceptable validity of 10 Hz GPS compared with radar (Beato et al., 2018; Roe et al., 2017; Sagiroglu et al., 2021), others found poor agreement under similar conditions (Akyildiz et al., 2022). Both lower-frequency GPS (5 Hz) and higher-frequency GPS (16 Hz) have also produced different results compared to the gold standard (Johnston et al., 2012; Lacome et al., 2019). However, more recent research showed that 10 Hz GPS is accurate to assess MSS compared to radar on a group level, while high limits of agreements indicate that accuracy lacks on an individual level (Altmann et al., 2024). LPS systems (20–45 Hz) demonstrated poor validity when compared with motion capture (Fleureau et al., 2020; Ogris et al., 2012), despite showing good reliability in most studies regarding LPS as well as GPS (Beato & de Keijzer, 2019; Coutts & Duffield, 2010; Fornasier-Santos et al., 2022; Hoppe et al., 2018; Johnston et al., 2014; Sagiroglu et al., 2021; Willmott et al., 2019). These findings are somewhat unexpected, given that LPS has been regarded as a valid tool for assessing other running metrics; however, Pino-Ortega et al. (2021) emphasized that its validity is highly influenced by the data processing methods used. Most importantly, the validity of these systems appears highly dependent on the methodological quality of the studies.

Video analysis through smartphone applications offers a relatively inexpensive and accessible way to assess sprint kinematics by recording time and distance. Two studies evaluating the MySprint app reported good validity for MSS in both male and female team-sport athletes as well as trained sprinters, along with good intraday reliability (Ghigiarelli et al., 2022; Romero-Franco et al., 2017). These findings suggest that smartphone apps can provide a valid and reliable method for MSS assessment; however, given the limited number of studies, further research is needed to confirm their applicability.

Because MSS is typically assessed during linear overground sprinting, outdoor environmental factors such as wind can influence the results. To reduce this variability, treadmill-based testing has been proposed as a standardized laboratory alternative (Highton et al., 2012). However, studies using motorized and non-motorized treadmills have reported poor convergent and criterion validity, with substantially lower MSS values compared to overground sprinting (Highton et al., 2012; Morin & Sève, 2011). This discrepancy is likely due to the higher resistance inherent to treadmill mechanics. Nevertheless, both intra- and interday reliability have been shown to be good (Highton et al., 2012).

In summary, the systematic review of methods to assess MSS in Paper III showed that besides radar and laser technologies, timing gates with 5- to 10-m split times are a practical alternative for field settings, provided appropriate sprinting distances are used. While smartphone applications also show promise, their limited investigation to date requires further investigation. Moreover, GPS and LPS as well as treadmill sprinting cannot yet be recommended as a substitute for overground MSS testing.

Based on the results of Papers II and III, Papers V and VI used valid and reliable methodology (radar for MSS and CPET for MAS) to assess the locomotor profile, i.e. MAS and MSS. The findings of those papers will be discussed in the following subchapter (Chapter 7.1.3).

7.1.3 Acute Responses and Chronic Adaptations Related to the Locomotor Profile (Paper V + VI)

Despite the established importance of HIIT and SIT for improving endurance performance, substantial interindividual variability in both acute responses and long-term adaptations persists among trained athletes (Cipryan et al., 2017; Lievens et al., 2020; Pickering & Kiely, 2019; Williams et al., 2017). Locomotor profiling through MAS, MSS, and their derivatives (ASR, SRR), has been proposed as a framework to explain these differences (Blondel et al., 2001; Sandford et al., 2021). In this regard, Papers V and VI of this dissertation addressed how different locomotor profiles influence acute physiological, biochemical, neuromuscular, and perceptual responses to HIIT (Paper V); and investigated the role of these profiles in moderating chronic adaptations to six weeks of HIIT versus SIT in runners (Paper VI).

The main findings of Papers V and VI were:

- Higher acute biochemical, neuromuscular, and athlete-reported measures for fatigue after a HIIT in endurance-type than speed-type athletes (Paper V)
- Speed-type athletes improve more in MAS and lactate thresholds than endurance types following six weeks of HIIT and SIT (Paper VI)

- Speed types increase $\dot{V}O_2$max more with HIIT and endurance types with SIT (Paper VI)
- The locomotor profile is adaptable through training (Paper VI)

Higher acute biochemical, neuromuscular, and athlete-reported measures for fatigue after a HIIT in endurance-type than speed-type athletes

Since athletes differ widely in their tolerance to HIIT, Paper V examined how locomotor profiles relate to acute cardiorespiratory, biochemical, neuromuscular, and athlete-reported responses during MAS-based HIIT, with the aim of improving training prescription and reducing overload risk. Biochemical and neuromuscular markers revealed clear ASR- and MSS-dependent responses. Athletes with lower ASR and MSS, i.e., endurance types, showed greater increases in creatine kinase (CK) and larger declines in countermovement jump (CMJ) height and reactive strength index (RSI), indicating higher muscle damage and neuromuscular fatigue after the HIIT than speed types (Baird et al., 2012). Impaired neuromuscular performance is closely linked to reduced muscle activation (Mendez-Villanueva et al., 2008), which aligns with our finding that athletes with a lower ASR, running at a higher relative intensity (%ASR), showed elevated markers of muscle damage (i.e., CK) and consequently reduced CMJ performance after HIIT. In contrast, Buchheit, Hader, et al. (2012) reported no influence of athletes' MAS or MSS on CMJ and drop jump changes in recreational team sport players, likely due to differences in protocol, as their repeated sprint design imposed a distinct form of stress compared to the short-format HIIT used in Paper V. Consistently, the strong correlations between %ASR and pre–post changes in CMJ height and RSI suggest that athletes with higher MAS but lower MSS, and thus higher %ASR, incur greater acute loads than those exercising at lower relative intensities, although the HIIT was individualized based on MAS. Differences between athletes may also relate to fiber typology, with higher ASR athletes (speed types) likely possessing more fast-twitch fibers and greater tolerance to metabolic stress (Parkhouse et al., 1985). Unlike biochemical and neuromuscular outcomes, heart rate recovery (HRR) was unrelated to ASR, contrasting with Del Rosso et al. (2017), possibly due to differences in protocols. Overall, these findings suggest that acute tolerance following MAS-based HIIT varies with locomotor profile, highlighting that ASR and MSS are key moderators of neuromuscular and biochemical load.

However, changes in RPE were not associated with ASR. This aligns with earlier findings showing comparable RPE between sprint- and endurance-oriented athletes, as well as between high- and low-ASR athletes following short-format HIIT (Buchheit, Hader, et al., 2012; Cipryan et al., 2017), whereas endurance athletes reported higher RPE after long-format HIIT (Cipryan et al., 2017). Such differences may be explained by the "peak-end rule", whereby experiences are judged largely by their most intense moment at the end, potentially influenced by the shorter final rest in short-format HIIT (Haines et al., 2020).

However, beyond RPE, athletes with lower ASR, i.e. endurance types, reported greater acute fatigue, reduced perceived physical performance capability and overall recovery, and higher muscular and overall stress (as assessed via the SRSS and a single item for fatigue), while emotional state and motivation did not differ between groups. This may reflect the resilience and intrinsic motivation of trained athletes, allowing them to maintain emotional balance despite physical strain, independent of the locomotor profile. Importantly, all athlete-reported responses returned to baseline within 24 h, suggesting that while acute perceptions of fatigue and recovery differ between locomotor profiles, longer-term athlete-reported outcomes might not.

In sum, the findings of Paper V indicate that an athlete's locomotor profile influences the tolerance to short-format HIIT, although the HIIT was individualized based on MAS. More specifically, endurance-type athletes, showed higher load markers as assessed via biochemical, neuromuscular, and athlete-reported outcomes. Recent studies showed that individualization of HIIT based on ASR produces more consistent acute responses compared to MAS-based HIIT (Bok, Gulin, Škegro, et al., 2023; Julio et al., 2020). However, since MAS-based HIIT is very common in practice, it is recommended to take the individual locomotor profile into account when prescribing short-format, MAS-based HIIT to avoid acute overload.

Speed-type athletes improve more in MAS and lactate thresholds than endurance types following six weeks of HIIT and SIT

Although both HIIT and SIT have shown to improve determinants of endurance performance, findings in trained athletes are inconsistent, reflecting substantial interindividual variability (Pickering & Kiely, 2019; Williams et al., 2017). To address this, *Paper VI* examined whether locomotor profiles moderate physiological and locomotor adaptations to six weeks of HIIT and SIT in trained runners, providing insights into individualized training strategies. In this regard, both interval training formats enhanced MAS and lactate thresholds more effectively in speed-type than in endurance-type athletes. The greater MAS improvements in speed types likely reflect their lower baseline MAS and higher adaptive potential. While repeated sprinting is often considered optimal for speed-type athletes (Sandford et al., 2021), our findings suggest that they also benefit from long-format HIIT. Still, their fiber-type composition may limit tolerance to high training volumes, highlighting the need for longitudinal monitoring of load and fatigue (Bellinger et al., 2020). In contrast, endurance-type athletes showed smaller increases in MAS and lactate thresholds, suggesting that increasing overall training volume and emphasizing continuous LIT (<vLT) may be more effective than raising HIIT volume for this group (Seiler, 2010).

Speed types increase $\dot{V}O_2max$ more with HIIT and endurance types with SIT

Moreover, Paper VI shows that six weeks of HIIT or SIT improve MAS but not $\dot{V}O_2max$ on a group-level in trained male and female runners. Interestingly, changes in $\dot{V}O_2max$ varied with locomotor profile: speed types improved more with HIIT, while endurance types improved more with SIT. This suggests that individual profiles can mask group-level effects. Genetic predisposition and muscle fiber typology are strong predictors of responsiveness to training (Meyler et al., 2021; Williams et al., 2017), explaining these findings. Since HIIT primarily promotes central adaptations , e.g., cardiac output, and SIT favors peripheral adaptations, e.g., angiogenesis, (Rosenblat et al., 2022) (see also Chapter 2.2.2), it is plausible that speed types, being potentially more peripherally limited at baseline, benefited more from HIIT, while endurance types, with potentially already high cardiac output, responded better to SIT. However, being hypothetical, future research should clarify whether these profile-specific responses are mediated by central versus peripheral mechanisms. Moreover, it is noteworthy to mention that SIT resulted in a substantially higher injury rate (SIT: 21.1%, HIIT: 5.9%). Although SIT provides a strong stimulus for improving MAS and MSS at the group level, as well as $\dot{V}O_2max$ in endurance-type athletes, its integration into training routines should be approached with caution.

The locomotor profile is adaptable through training

Additionally, Paper VI indicates that locomotor profiles are adaptable through training. On a group level, SIT induced concurrent gains in MAS and MSS without altering ASR or SRR, whereas HIIT increased MAS alone, thereby reducing both reserves. Similar decreases in ASR after HIIT have been reported in soccer players by Dai and Xie (2023), supporting the notion that locomotor profiles can be modified by specific training stimuli. Importantly, these changes were largely influenced by baseline MSS: runners in the SIT group with a higher MSS and ASR, showed higher ASR reductions, i.e. a shift towards hybrid type, than those with lower MSS, while baseline levels did not predict adaptations of the profile in the HIIT group. Moreover, speed-type athletes in both groups showed larger SRR reductions, suggesting a shift toward a more hybrid locomotor profile, whereas endurance types remained more stable. Given that substantial muscle fiber type shifts are unlikely within six weeks of training, these adaptations likely reflect differences in exercise habits and conditioning prior to the intervention rather than typology (Dai & Xie, 2023). Collectively, the results demonstrate that locomotor profiles are not fixed traits but can adapt, particularly in less trained athletes who benefit from both SIT and HIIT through MAS gains and subsequent SRR reductions.

Overall, Paper VI shows that six weeks of HIIT and SIT improve endurance performance differently depending on athletes’ locomotor profiles. Speed types achieve greater gains in MAS and lactate thresholds than endurance types, likely due to lower baseline MAS and higher adaptive potential, indicating they benefit from both HIIT and SIT. Also changes in $\dot{V}O_2max$ are profile-specific, with speed-types responding better to HIIT and endurance-types to SIT, potential due to central versus peripheral adaptation pathways. Finally, the locomotor profile itself proved to be adaptable: SIT improved both MAS and MSS, while HIIT selectively enhanced MAS and reduced reserves, with baseline MSS shaping responses and speed-types shifting toward a more hybrid profile. These findings highlight that endurance adaptations and locomotor profiles are not fixed but depend on both training format and athlete characteristics, underscoring the value of individualized training strategies.

Together, the findings of Paper V and Paper VI point out the importance of evaluating athletes' locomotor profiles to understand individual acute responses as well es chronic adaptations to training. Overall, the outcomes of Papers I to VI highlight the value of locomotor profiling for performance assessments and optimizing training procedures. In this regard, Figure 2.2 can be updated in Figure 7.1 by MSS (blue) and MAS (pink) as well as an additional influence of sprint training on aerobic power and capacity. After addressing the results of Papers I to VI in light of their limitations and highlighting open research questions (Chapter 7.2), practical applications are derived based on the main findings and the studies' limitations in Chapter 7.3.

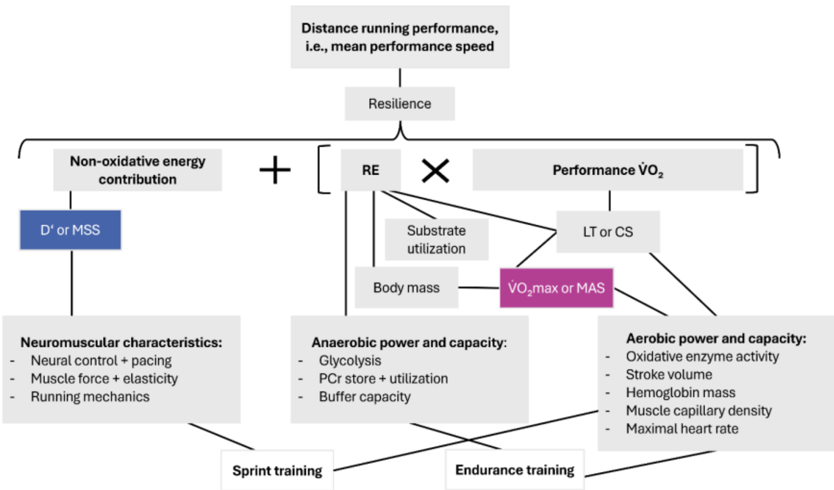

Figure 7.1: Determinants of running performance, adapted from Jones (2023); Joyner and Coyle (2008); Paavolainen, Häkkinen, et al. (1999). RE – running economy; $\dot{V}O_2$ – oxygen consumption; D' – curvature constant; LT – lactate threshold; CS – critical speed; $\dot{V}O_2max$ – maximal oxygen uptake; MSS – maximal sprinting speed; MAS – maximal aerobic speed.

7.2 Limitations and Future Research

Across Papers I to VI, several methodological and contextual limitations must be acknowledged, which lead to open research questions. A limitation of Paper I relates to the concerns of using ċLamax as a marker of maximal power of the glycolytic metabolism. As discussed in more detail in Chapter 7.1.1, recent critiques highlight methodological and conceptual issues, including uncertainty about achieving true maximal flux, short duration of peak flux, absence of clear attainment criteria, errors in correcting for lactate clearance, and neglect of oxidative contributions (Langley et al., 2025; Wackerhage et al., 2025). Given these concerns, along with the methodological effort required and the strong correlations found between ċLamax and MSS in Paper I, MSS appears to be a more practical and sufficient marker capturing both maximal anaerobic power and neuromuscular-mechanical capabilities. However, these interrelations should be looked into in the future in more detail with homogeneous, elite athletes in order to draw confident conclusions.

A recurring limitation is the relatively small sample sizes, especially in Papers I, II, and V, leading to a higher risk of missing a true effect. Recruiting highly trained athletes is challenging, and heterogeneity in age, training experience, and maturation status (Mota et al., 2002) might further limit generalizability. These limitations together with male-dominated samples and non-gold standard reference methods also occur in many of the included studies in the systematic review (Paper III), which in many cases led to a lower ranking in the methodological quality assessment and thus less consideration in the interpretation of their findings. However, it is noteworthy to mention that most original studies in this thesis (Papers I, IV, V, VI) included male and female athletes aiming to close the gaps in male-centered research. Another limitation refers to differing environmental conditions (e.g., indoor vs. outdoor tracks, varying times of day) of some performance tests in Paper I and II, which may have affected outcomes (Chtourou & Souissi, 2012; Haugen & Buchheit, 2016). For a broader generalizability, future studies should aim for larger, more homogenous cohorts and greater standardization of testing environments. Regarding valid and reliable assessment of MAS and MSS and to advance athlete profiling, future research must establish sport-, sex-, and fitness-specific studies of validity and reliability of testing methods. Most importantly, since locomotor profiling aims to be directly applicable into regular procedures of athletes, further methods and technologies should be developed and evaluated in future studies to enable valid and reliable testing during training or competitions (i.e., races or matches), while minimizing additional (testing) load for athletes.

Moreover, the regression equations in Paper IV are limited to the stage duration and increments used in the data set as well as soccer players as a target population, limiting applicability for other protocols or types of sports. Although the overall sample size was very large (N=2648), only 5% of the sample consisted of female athletes (n=124) which may influence the significance of sex as a predictor variable. Since predictions are very specific to the underlying data, future research should evaluate v_{peak} predictors across protocols and athlete populations (i.e., more female athletes and different types of sports) to improve applicability and transferability.

Also, locomotor profiling itself bears some constraints as discussed in Chapter 7.1.2. While the main components, MAS and MSS, should always be considered in evaluating profiles, e.g., categorizing athletes as speed or endurance types, using ASR or SRR can depend on the heterogeneity of the sample (see Chapter 7.1.1). Although locomotor profiling via the SRR has been proposed as a valuable modification, particularly for normalizing ASR (Sandford, Kilding, et al., 2019), Paper V did not examine SRR as a predictor of acute responses to HIIT. This was due to statistical constraints, as the prerequisites for calculating valid ratios were not achieved within the data (Curran-Everett, 2013). Therefore, ASR but also MAS and MSS were included as potential predictors to get a more detailed picture of how the locomotor profile might influence the acute responses. Although Paper V pointed towards locomotor profiling being a useful tool for evaluating acute responses to HIIT, the limited number of studies examining acute athlete-reported outcomes in relation to locomotor profiles highlights that further research is warranted to address this gap. Moreover, while the present findings provide initial insights into delayed athlete-reported responses (fatigue, stress, recovery) 24 h post-HIIT, longitudinal studies are needed to integrate both objective and subjective load markers, thereby clarifying long-term differences in adaptation and load regulation across locomotor profiles.

In longitudinal studies, effective monitoring of training often represents a major challenge. In Paper VI, HR and pace monitoring via an online platform combined with weekly feedback (and additional feedback anytime if necessary) were applied to keep the compliance high and ensure that the training was performed as prescribed. However, maintaining prescribed intensities proved challenging, particularly in the SIT group, where fluctuations in fatigue and motivation were evident. In the future, the use of advanced monitoring approaches, such as real-time wearable-based feedback, may help improve adherence and ensure more consistent execution of training intensities in future interventions. Furthermore, both groups trained for six weeks using the same pyramidal intensity distribution to allow direct comparison of HIIT and SIT adaptations. It was previously suggested, that besides different training formats, such as HIIT versus SIT, different training intensity distributions should be chosen depending on the locomotor profile to elicit favorable adaptions while avoiding overload (Sandford et al., 2021; Zinner & Sperlich, 2018). Future studies should therefore examine whether individualized intensity distributions may optimize adaptations for different locomotor types. In this regard, both physical and athlete-reported measures of training load should be systematically assessed in relation to locomotor profile in longitudinal studies. Such investigations could clarify how different athletes respond to varying forms of HIIT or intensity distributions regarding load and adaptations, and provide an individualized basis for tailoring training prescriptions.

Finally, in the presented studies, different samples were used regarding training background and fitness level (i.e., highly trained runners in Papers I and V, highly trained soccer players in Papers II and IV, trained runners in Paper VI). Therefore, the locomotor profiles were evaluated within the sample, since the literature lacks regarding normative values for different types of sports and fitness levels with respect to benchmarks for categorizing athletes as speed, hybrid, or endurance types based on the ASR concept. Future studies should urgently fill this gap to help guiding researchers but also practitioners in evaluating their athletes' physical qualities and improving the application of locomotor profiling. Most importantly, future research on this topic may enhance both the scientific understanding and the practical application of studies' findings. The practical implications based on the studies presented in this thesis are outlined in the following chapter (Chapter 7.3).

7.3 Practical Applications

In addition to highlighting directions for future research, the studies presented in this dissertation also provide findings with direct practical applicability, as the overarching aim is to conduct applied interdisciplinary research that links theoretical knowledge with evidence-based applications (see Chapter 2.1). Because profiling holds relevance not only in research but also in applied sport settings, it is important to translate the findings into practice. Understanding the limitations and possibilities of locomotor profiling is essential for tailoring training and optimizing athlete development. The following subchapter therefore outlines how the studies in this dissertation can inform practitioners in applying profiling their athletes effectively. Figure 7.1 provides an overview of the practical applications based on the findings of this thesis.

Firstly, the findings of Paper I highlight the practical value of physiological and locomotor profiling for differentiating between sprinting and running disciplines in adolescents and young adults. Sprinters demonstrated stronger anaerobic and neuromuscular-mechanical capacities, while middle-distance runners exhibited higher aerobic markers, and 400-m runners, particularly those with superior performance levels, combined both profiles. Such differentiation provides practitioners with a framework for identifying individual strengths and weaknesses, which can be applied in contexts such as talent identification or longitudinal monitoring of adaptations. Knowledge of an athlete's specific profile can further guide training design, either by targeting characteristics that require development (e.g., enhancing aerobic capacity through higher training volumes at lower intensities) or by reinforcing existing strengths (e.g., developing speed and power through lower volumes at higher intensities). Importantly, while both physiological and locomotor approaches offer comparable insights into aerobic and anaerobic(-mechanical) capacities, locomotor profiling provides the added advantage of directly informing individualized training prescriptions, such as tailoring HIIT based on the ASR. Moreover, as previously discussed (Chapter

7.1.1), considering the limitations of ċLamax, as well as the methodological demands and the strong correlations observed between ċLamax and MSS in Paper I, MSS emerges as a more practical and comprehensive marker of both anaerobic power and neuromuscular-mechanical capacities. Consequently, locomotor profiling offers a more practical yet equally meaningful approach in comparison to physiological profiling.

Secondly, the results of Papers II–IV provide important practical guidance for selecting valid and reliable methods to assess MAS and MSS, which form the basis of locomotor profiling. For MAS, Paper II showed that true MAS (i.e., the speed at the onset of the $\dot{V}O_2$ plateau) was substantially overestimated by other definitions, and that the UMTT and 1500-m TT showed limited validity for male soccer players, with deviations from true MAS exceeding typical training-induced improvements. Consequently, training prescriptions based on these tests may unintentionally induce higher intensities than intended, increasing the risk of overload or injury. To address this, practitioners are advised to either apply regression equations derived from gold-standard laboratory methods or adapt time-trial distances to the fitness level, sex, and sport-specific demands of the athletes (e.g., 1200–1400 m for team sport athletes, 1500–2000 m for endurance runners). Moreover, the systematic review (Paper III) showed that continuous incremental field tests and shuttle runs are not suitable for estimating MAS accurately. For MSS, radar or laser measurements remain the most valid approaches, while timing gates with short split times (5 or 10 m) or smartphone-based video analysis offer practical alternatives with sufficient accuracy. By contrast, GPS-derived speed and treadmill sprinting fail to capture true MSS. From an applied perspective, shorter sprint distances (20–40 m) are more appropriate for recreational and team sports athletes, whereas trained sprinters may require 40–70 m sprints to reach MSS. Importantly, both the selection of methods and the interpretation of MAS, MSS, and ASR must be tailored to the sport-specific context.

In elite sports, exercise testing needs to be time efficient and if possible, with as little strain as possible. Since in many running-based sports and especially in soccer incremental running tests are regularly performed to assess endurance performance via lactate thresholds, Paper IV aimed to estimate v_{peak} as a proxy of maximal aerobic performance with submaximal markers. In this regard, Paper VI adds practical applications for aerobic performance monitoring, demonstrating that submaximal markers such as vL4, alongside sex and age, can serve as reliable and accessible predictors of v_{peak} regardless of testing environment (field or treadmill). Even in the absence of lactate thresholds, submaximal fractional utilization of HRmax or estimated HRmax (i.e., 220-age) allows for v_{peak} predictions with errors smaller than the typical smallest worthwhile change (~1 km/h). Such approaches provide practitioners with simple and low-burden alternatives to estimate maximal aerobic performance, enabling individualized training prescriptions and regular performance monitoring without extensive laboratory testing. Based on those results, we could provide an easily accessible online-calculator (https://vpeak.shinyapps.io/vpeak_prediction/).

However, it is important to consider that v_{peak} overestimates true MAS by around 1 km/h (see Paper III) and therefore the relative intensity for prescribing training based on v_{peak} should be altered to avoid an undesirably high load (e.g., 105% v_{peak} while 110% MAS). In sum, Papers II to IV show that differences in MAS or MSS estimation methods substantially alter ASR and thus the prescribed training intensity or evaluation of performance progressions over time, underscoring the need for population-specific validity testing and consistent application of methods in both research and practice.

With regard to the third research aim, the findings of Papers V and VI provide important practical insights into how acute responses and chronic adaptations to training are influenced by the locomotor profile. Coaches and practitioners should take into account that runners with a lower ASR (and MSS), i.e., endurance types, experience higher acute internal loads, both objective and athlete-reported, during short-format HIIT, even when intensity is normalized to MAS. This is because such athletes are required to work at a higher relative percentage of their ASR, which partly explains interindividual differences in training responses. Therefore, this format (2 sets of 20x 15 s at 110% MAS with 15 s passive rest) should only be incorporated with caution and to a lesser extent into training routines of endurance-type athletes, while speed-type athletes show a higher tolerance. From a practical perspective, this highlights the importance of tailoring training stimuli to the athlete's locomotor profile. Moreover, prescribing short-format HIIT based on %ASR may yield more homogenous load responses across athletes with different ASR profiles.

In terms of chronic adaptations, Paper VI showed that SIT can serve as a time-efficient method to increase both MAS and MSS in trained athletes. However, the higher injury-related dropout rate in the SIT group suggests that the mechanical load of repeated sprint efforts may exceed tissue tolerance for some individuals, even when perceived effort is comparable to HIIT (i.e., RPE). This finding underlines the need to balance training efficiency with injury risk when implementing SIT in practice. Importantly, speed-type athletes responded favorably to HIIT (4–6x 4 min at 90–95% MAS with 2 min rest at low intensity) regarding $\dot{V}O_2max$, demonstrating that longer intervals may complement sprint-specific work, while endurance-type runners might require higher training volumes or additional low-intensity work to meaningfully improve aerobic endurance markers. SIT (6-8x 20 s all-out sprinting with 3 min rest at low intensity), in contrast, may act as a useful stimulus to enhance peripheral adaptations and $\dot{V}O_2max$ as well as MSS in endurance types. Overall, the marked interindividual variability in both acute responses and training adaptations underscores the value of locomotor profiling for guiding training prescription. Also for research applications, it will be important to consider how the locomotor profile shapes acute and chronic responses, as this may affect the interpretation of outcomes relative to the study's primary objective and to avoid biased results. Additionally, changes in ASR and SRR across the six-weeks intervention period further demonstrate that locomotor profiles are not static but adaptable, supporting the application of targeted training stimuli to shape an athlete's speed-endurance characteristics in accordance with race demands or seasonal objectives.

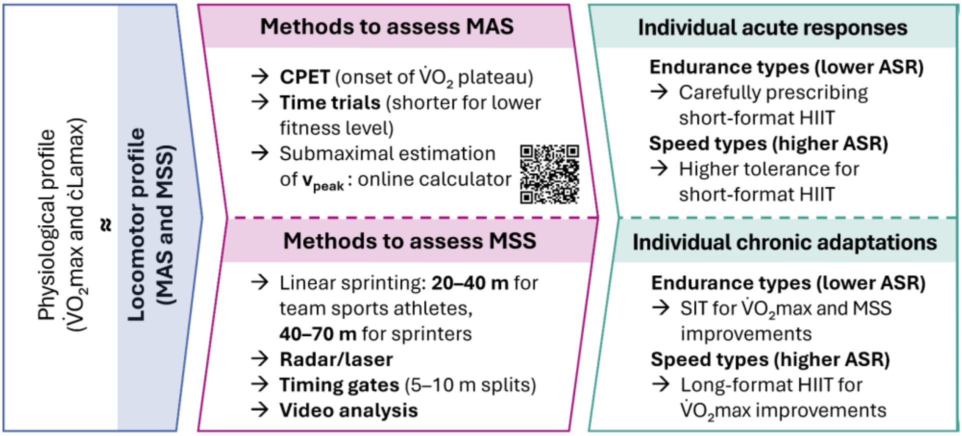

Figure 7.2: Overview practical applications based on findings of this thesis. MAS – maximal aerobic speed; CPET – cardiopulmonary exercise testing; $\dot{V}O_2$ – oxygen uptake; v_{peak} – peak speed in incremental running test, i.e., proxy of maximal aerobic performance; MSS – maximal sprinting speed; ASR – anaerobic speed reserve; HIIT – high-intensity interval training; $\dot{V}O_2max$ – maximal oxygen uptake; SIT – sprint interval training.

This subchapter outlined several practical applications derived from the six studies of this thesis with a basis from the broader body of literature, offering insights for both researchers and practitioners. Based on the discussion of the thesis' main aims, the studies' limitations and the derived practical applications, the final chapter concludes the thesis.

8 Conclusion

This thesis evaluated the importance of profiling for individualized endurance testing and training in running-based sports. The three main aims were:

A. To investigate the value and relationship between physiological and locomotor profiling across running disciplines.
B. To evaluate and systematically review the validity and reliability of tests to assess MAS and MSS in running-based sports.
C. To examine the role of locomotor profiles in explaining acute responses and chronic adaptations to different HIIT formats.

With respect to the first aim, the results demonstrate that athletes from different running disciplines display distinct physiological (based on $\dot{c}$Lamax and $\dot{V}O_2max$) and locomotor profiles (based on ASR, i.e., MSS and MAS). Sprinters were characterized by greater anaerobic-mechanical but lower aerobic capacities, while middle-distance runners showed the inverse pattern. Notably, 400-m runners, particularly those with superior competition performance, combined both high aerobic and anaerobic-mechanical characteristics. These findings highlight the discriminative value of profiling, as the ASR can effectively classify athletes into speed-, hybrid-, or endurance-oriented profiles, with 400-m runners spanning all categories. While both physiological and locomotor profiling provide valuable insights, the findings of this thesis suggest that locomotor profiling is more applicable in practice. The strong correlations observed between physiological markers such as $\dot{c}$Lamax and locomotor measures like MSS indicate that similar information can be obtained with less methodological complexity. MSS, in particular, offers a practical and comprehensive marker of anaerobic power and neuromuscular-mechanical capacity. Consequently, locomotor profiling emerges as the more feasible approach for applied settings, while still complementing physiological profiling in research contexts.

Regarding the second aim, this thesis provides novel insights into the validity and reliability of testing methods for MAS and MSS, i.e., the components of ASR. The findings confirm that varying definitions of MAS yield divergent results and that common field tests are insufficiently valid in estimating MAS, often leading to unintended overprescription of training intensity based on MAS estimates. Laboratory-based assessment of MAS via $\dot{V}O_2$ kinetics and the identification of the $\dot{V}O_2$ plateau appears most appropriate, although adjusted time-trial distances tailored to the athlete's background may provide practical alternatives. When keeping in mind that the training intensity must be adjusted when using v_{peak} as an aerobic performance marker, evidence from Paper VI demonstrated that submaximal markers such as vL4, combined with age and sex, can serve as practical predictors of v_{peak}

in professional soccer players, while preventing high load when testing to exhaustion. This emphasizes the value of accessible physiological markers for performance monitoring and training prescription. For MSS, radar or laser systems remain the gold standard, but timing gates or video analysis offer sufficiently valid field-based methods, particularly when sprint distances are adapted to the athlete's level and sport-specific demands. The systematic review further highlights the critical importance of selecting valid and reliable methods, as inconsistent estimation of MAS or MSS substantially alters the ASR and, consequently, prescribed training intensities. Collectively, these findings reinforce the need for accurate, sport-specific, and consistent testing protocols when profiling athletes.

In relation to the third aim, the studies highlight the relevance of the locomotor profile in shaping both acute responses and chronic adaptations to interval training. Athletes with lower ASR and MSS, i.e. endurance types, displayed higher internal load responses, both physiological and athlete-reported, during short-format HIIT, whereas athletes with higher ASR, i.e. speed types, tolerated the HIIT with comparatively lower internal physiological and athlete-reported load responses. Moreover, over six weeks of training, both HIIT and SIT improved MAS in trained runners, though large interindividual variability emerged. Speed-type athletes tended to respond more strongly to HIIT, showing improvements in MAS, lactate thresholds, and $\dot{V}O_2max$, while endurance-type athletes benefitted more from SIT, particularly in MSS and $\dot{V}O_2max$ adaptations. These findings underline that locomotor profiles are not only descriptive but also predictive of training responsiveness, supporting their use for tailoring training prescriptions. The adaptability of the locomotor profile, i.e., ASR and SRR, across the intervention period further demonstrates the potential of targeted stimuli to shift an athlete's speed-endurance balance according to race demands or seasonal goals. However, locomotor profiling provides one approach in helping to understand individual acute responses and chronic adaptations. Several factors such as genetics, physiological, and contextual factors (as discussed in Chapter 2.3) can influence the responsiveness further.

To conclude, this thesis provides valuable contributions to the current body of knowledge by highlighting the importance of profiling, and in particular locomotor profiling, in advancing individualized endurance testing and training in running-based sports, beyond the traditional determinants of endurance performance. By integrating physiological and locomotor perspectives, evaluating valid and reliable testing protocols, and applying profiling to guide individualized training strategies, this work advances the understanding of how athletes differ in their performance characteristics and training adaptations. In doing so, this thesis offers practical recommendations for researchers and practitioners concerned with topics such as athlete profiling, performance monitoring, and individualized training prescription. It should be noted, however, that the applicability of profiling is always influenced by the methodological choices and the specific populations studied. While this thesis advances the understanding of how athletes differ in their physiological and locomotor characteristics, training adaptations remain complex and are shaped by a variety of internal and external factors. Profiling therefore represents one important piece of the puzzle, complementing other or traditional determinants of performance. As this field is still developing, a number of questions remain open for future research. Promising directions include refining population-specific protocols for MAS and MSS assessment, exploring the predictive value of locomotor profiles for load monitoring, and integrating profiling approaches into long-term athlete development models. Ultimately, by extending and contextualizing the findings of this dissertation, future work can contribute to an even deeper understanding of endurance performance and support the ongoing evolution of individualized monitoring and training practices.

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Appendices

1 Paper III Supplementary Table 1: PRISMA 2020 checklist.

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			Page
Title	1	Identify the report as a systematic review.	1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3-4
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	4
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	5-6
Infor-mation sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	6
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	6-7; Sup-plemen-tary B
Selection process	8	Specify the methods used to decide whether a study met the inclu-sion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked inde-pendently, and if applicable, details of automation tools used in the process.	7
Data col-lection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automa-tion tools used in the process.	7
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome do-main in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	7–8
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). De-scribe any assumptions made about any missing or unclear infor-mation.	7–8, Tables 1 and 2
Study risk of bias as-sessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	8, Sup-plemen-tary C
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Tables 1 and 2

Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	7–8
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	7-8
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	7–8, Tables 1 and 2
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	7-8
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	n.a.
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	n.a.
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	8
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	8
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Figure 1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Figure 1
Study characteristics	17	Cite each included study and present its characteristics.	9, Tables 1 and 2
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	10, Table 3
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables.	10–11, Table 2
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	10–11
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	10, Supplementary C
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	n.a
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	n.a.
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Table 3
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	9-10

DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	16-26
	23b	Discuss any limitations of the evidence included in the review.	27
	23c	Discuss any limitations of the review processes used.	27
	23d	Discuss implications of the results for practice, policy, and future research.	27-29
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	5
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	5
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	n.a.
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	31
Competing interests	26	Declare any competing interests of review authors.	31
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	31

2 Paper III Supplementary Information 1: Search Terms PubMed

(validity OR logical OR criterion OR convergent OR discrimination OR construct OR "gold standard" OR level OR standard OR reliability OR repeatability OR reproducibility OR "measurement error" OR consistency OR "smallest worthwhile change" OR "minimal detectable change", OR "typical error" OR usefulness OR „minimal important difference“ OR „standard error“ OR relationship OR relation OR association OR correlation)

AND

(„max* aerobic speed" OR MAS OR “maximal aerobic velocity” OR „velocity at $\dot{V}O_2max$" OR „velocity associated with $\dot{V}O_2max$" OR v$\dot{V}O_2max$ OR „max* sprinting speed“ OR „max* speed“ OR MSS OR „max* velocity“ OR „peak speed“ OR „anaerobic speed reserve“ OR “anaerobic velocity reserve” OR ASR)

AND

(sport* OR athlete OR „team sport“ OR „individual sport“)

3 Paper III Supplementary Table 2: Assessment of methodological quality based on the boxes 6 – 9a of the COSMIN checklist.

	Akyildiz et al. [66]	Barbero-Alvarez et al. [32]	Barbero-Alvarez et al. [55]	Beato et al. [18]	Beato et al. [67]	Bellenger et al. [33]	Benhammou et al. [51]	Bernard et al. [34]	Berthoin et al. [35]
Box 6. Reliability									
Design requirements									
1. Were patients stable in the interim period on the construct to be measured?	3	NA	NA	3	1	NA	3	NA	NA
2. Was the time interval appropriate?	3	NA	NA	3	1	NA	3	NA	NA
3. Were the test conditions similar for the measurements? e.g. type of administration, environment, instructions	3	NA	NA	3	3	NA	3	NA	NA
Statistical methods									
4. For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	3	NA	NA	1	3	NA	3	NA	NA
Other									
8. Were there any other important flaws in the design or statistical methods of the study?	3	NA	NA	3	3	NA	3	NA	NA
Box 7. Measurement error									
Design requirements									
1. Were patients stable in the interim period on the construct to be measured?	3	NA	NA	3	1	NA	3	NA	NA
2. Was the time interval appropriate?	3	NA	NA	3	1	NA	3	NA	NA
3. Were the test conditions similar for the measurements? (e.g. type of administration, environment, instructions)	3	NA	NA	3	3	NA	3	NA	NA

Statistical methods									
4. For continuous scores: Was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC) or Limits of Agreement (LoA) calculated?	3	NA	NA	2	3	NA	3	NA	NA
Other									
6. Were there any other important flaws in the design or statistical methods of the study?	3	NA	NA	3	3	NA	3	NA	NA
Box 8. Criterion validity									
Statistical methods									
1. For continuous scores: Were correlations, or the area under the receiver operating curve calculated?	3	3	3	3	3	3	3	3	3
Other									
3. Were there any other important flaws in the design or statistical methods of the study?	3	1	1	3	3	3	3	1	1
Box 9a. Convergent validity									
Design requirements									
1 Is it clear what the comparator instrument(s) measure(s)?	3	3	2	3	3	3	3	3	3
2 Were the measurement properties of the comparator instrument(s) sufficient?	3	3	2	3	3	3	3	3	3
Statistical methods									
3 Were design and statistical methods adequate for the hypotheses to be tested?	3	3	3	3	3	3	3	3	3

3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate, and NA = not applicable.

Paper III Supplementary Table 2: Continued.

	Berthon et al. [36]	Berthon et al. [37]	Billat et al. [6]	Cappa et al. [52]	Carminatti et al. [38]	Chahal et al. [68]	Ghigiarelli et al. [71]	Clark et al. [56]	Coutts and Duffield [69]	Čović et al. [14]	Da Silva and Machado [39]
Box 6. Reliability											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	NA	3	NA	3	3	NA	3	3	NA
2. Was the time interval appropriate?	NA	NA	NA	1	NA	3	3	NA	3	3	NA
3. Were the test conditions similar for the measurements? e.g. type of administration, environment, instructions	NA	NA	NA	3	NA	3	3	NA	3	3	NA
Statistical methods											
4. For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	NA	NA	NA	1	NA	3	3	NA	0	3	NA
Other											
8. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	NA	3	NA	3	3	NA	1	3	NA
Box 7. Measurement error											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	NA	3	NA	3	3	NA	3	3	NA
2. Was the time interval appropriate?	NA	NA	NA	1	NA	3	3	NA	3	3	NA
3. Were the test conditions similar for the measurements? (e.g. type of administration, environment, instructions)	NA	NA	NA	3	NA	3	3	NA	3	3	NA

Statistical methods											
4. For continuous scores: Was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC) or Limits of Agreement (LoA) calculated?	NA	NA	NA	2	NA	3	3	NA	0	3	NA
Other											
6. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	NA	3	NA	3	3	NA	1	3	NA
Box 8. Criterion validity											
Statistical methods											
1. For continuous scores: Were correlations, or the area under the receiver operating curve calculated?	3	3	3	3	3	0	3	3	3	3	3
Other											
3. Were there any other important flaws in the design or statistical methods of the study?	3	3	3	3	3	3	3	1	0	3	3
Box 9a. Convergent validity											
Design requirements											
1 Is it clear what the comparator instrument(s) measure(s)?	3	3	3	3	3	3	3	3	3	3	3
2 Were the measurement properties of the comparator instrument(s) sufficient?	3	3	3	3	3	2	3	3	3	3	3
Statistical methods											
3 Were design and statistical methods adequate for the hypotheses to be tested?	3	3	3	3	3	3	3	3	1	3	3

3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate, and NA = not applicable.Paper IIISupplementary Table 2: Continued.

	Darendeli et al. [40]	Dillon et al. [41]	Dittrich et al. [42]	Djaoui et al. [19]	Ferro et al. [57]	Fleureau et al. [58]	Fornasier-Santos et al. [70]	Foster et al. [43]	Helland et al. [65]	Highton et al. [72]	Hoppe et al. [73]
Box 6. Reliability											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
2. Was the time interval appropriate?	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
3. Were the test conditions similar for the measurements? e.g. type of administration, environment, instructions	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
Statistical methods											
4. For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	NA	NA	NA	NA	NA	NA	0	NA	1	0	0
Other											
8. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
Box 7. Measurement error											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
2. Was the time interval appropriate?	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
3. Were the test conditions similar for the measurements? (e.g. type of administration, environment, instructions)	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
Statistical methods											

4. For continuous scores: Was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC) or Limits of Agreement (LoA) calculated?	NA	NA	NA	NA	NA	NA	3	NA	2	3	2
Other											
6. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	NA	NA	NA	NA	3	NA	3	3	3
Box 8. Criterion validity											
Statistical methods											
1. For continuous scores: Were correlations, or the area under the receiver operating curve calculated?	3	3	3	0	0	3	0	3	NA	3	0
Other											
3. Were there any other important flaws in the design or statistical methods of the study?	3	3	3	3	3	0	3	3	NA	3	3
Box 9a. Convergent validity											
Design requirements											
1 Is it clear what the comparator instrument(s) measure(s)?	3	3	3	3	3	3	3	3	NA	3	3
2 Were the measurement properties of the comparator instrument(s) sufficient?	3	3	3	3	3	3	3	3	NA	3	1
Statistical methods											
3 Were design and statistical methods adequate for the hypotheses to be tested?	3	3	3	3	3	1	3	3	NA	3	3

3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate, and NA = not applicable.

Paper III Supplementary Table 2: Continued.

	Johnston et al. [74]	Johnston et al. [75]	Lacome et al. [15]	Lacour et al. [44]	Laursen et al. [54]	Lopes et al. [45]	Lorenzen et al. [46]	Lundquist et al. [47]	Massard et al. [59]	Morin and Sève [60]	Ogris et al. [61]
Box 6. Reliability											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
2. Was the time interval appropriate?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
3. Were the test conditions similar for the measurements? e.g. type of administration, environment, instructions	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
Statistical methods											
4. For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
Other											
8. Were there any other important flaws in the design or statistical methods of the study?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
Box 7. Measurement error											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
2. Was the time interval appropriate?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
3. Were the test conditions similar for the measurements? (e.g. type of administration, environment, instructions)	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA

Statistical methods											
4. For continuous scores: Was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC) or Limits of Agreement (LoA) calculated?	3	3	NA	NA	3	NA	NA	NA	NA	NA	NA
Other											
6. Were there any other important flaws in the design or statistical methods of the study?	3	3	NA	NA		NA	NA	NA	NA	NA	NA
Box 8. Criterion validity											
Statistical methods											
1. For continuous scores: Were correlations, or the area under the receiver operating curve calculated?	3	3	0	3	NA	3	0	3	0	3	0
Other											
3. Were there any other important flaws in the design or statistical methods of the study?	0	0	0	3	NA	3	3	3	3	1	1
Box 9a. Convergent validity											
Design requirements											
1 Is it clear what the comparator instrument(s) measure(s)?	3	3	3	3	NA	3	3	3	3	3	3
2 Were the measurement properties of the comparator instrument(s) sufficient?	3	3	3	3		3	3	3	3	3	3
Statistical methods											
3 Were design and statistical methods adequate for the hypotheses to be tested?	0	0	0	3	NA	3	3	3	3	3	1

3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate, and NA = not applicable.

Paper III Supplementary Table 2: Continued.

	Pallarés et al. [48]	Paradisis et al. [49]	Riboli et al. [7]	Riboli et al. [50]	Roe et al. [62]	Romero-Franco et al. [76]	Sagiroglu et al. [77]	Sandford et al. [12]	Sangan et al. [13]	Schnitzler et al. [53]	Simpering-ham et al. [17]
Box 6. Reliability											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	NA	NA	NA	3	3	NA	3	3	3
2. Was the time interval appropriate?	NA	NA	NA	NA	NA	3	3	NA	3	3	3
3. Were the test conditions similar for the measurements? e.g. type of administration, environment, instructions	NA	NA	NA	NA	NA	3	3	NA	3	3	3
Statistical methods											
4. For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	NA	NA	NA	NA	NA	0	0	NA	3	3	3
Other											
8. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	NA	NA	NA	1	3	NA	3	3	3
Box 7. Measurement error											
Design requirements											
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	NA	NA	NA	3	3	NA	3	3	3
2. Was the time interval appropriate?	NA	NA	NA	NA	NA	3	3	NA	3	3	3

3. Were the test conditions similar for the measurements? (e.g. type of administration, environment, instructions)	NA	NA	NA	NA	NA	3	3	NA	3	3	3
Statistical methods											
4. For continuous scores: Was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC) or Limits of Agreement (LoA) calculated?	NA	NA	NA	NA	NA	2	3	NA	2	2	3
Other											
6. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	NA	NA	NA	1	3	NA	3	3	3
Box 8. Criterion validity											
Statistical methods											
1. For continuous scores: Were correlations, or the area under the receiver operating curve calculated?	3	3	3	3	3	3	3	3	3	3	NA
Other											
3. Were there any other important flaws in the design or statistical methods of the study?	3	3	3	3	0	1	3	1	3	3	NA
Box 9a. Convergent validity											
Design requirements											
1 Is it clear what the comparator instrument(s) measure(s)?	3	3	3	3	3	3	3	3	3	3	NA
2 Were the measurement properties of the comparator instrument(s) sufficient?	3	3	3	3	3	3	3	3	3	3	NA
Statistical methods											
3 Were design and statistical methods adequate for the hypotheses to be tested?	3	3	3	3	1	1	3	1	3	3	NA

Paper III Supplementary Table 2:Continued.

	Thron et al. [10]	Vescovi [62]	Willmott et al. [78]	Young et al. [64]	Zabaloy et al. [79]	Zabaloy et al. [80]
Box 6. Reliability						
Design requirements						
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	3	NA	3	3
2. Was the time interval appropriate?	NA	NA	3	NA	3	3
3. Were the test conditions similar for the measurements? e.g. type of administration, environment, instructions	NA	NA	3	NA	3	3
Statistical methods						
4. For continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	NA	NA	3	NA	3	3
Other						
8. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	3	NA	3	3
Box 7. Measurement error						
Design requirements						
1. Were patients stable in the interim period on the construct to be measured?	NA	NA	3	NA	3	3
2. Was the time interval appropriate?	NA	NA	3	NA	3	3
3. Were the test conditions similar for the measurements? (e.g. type of administration, environment, instructions)	NA	NA	3	NA	3	3

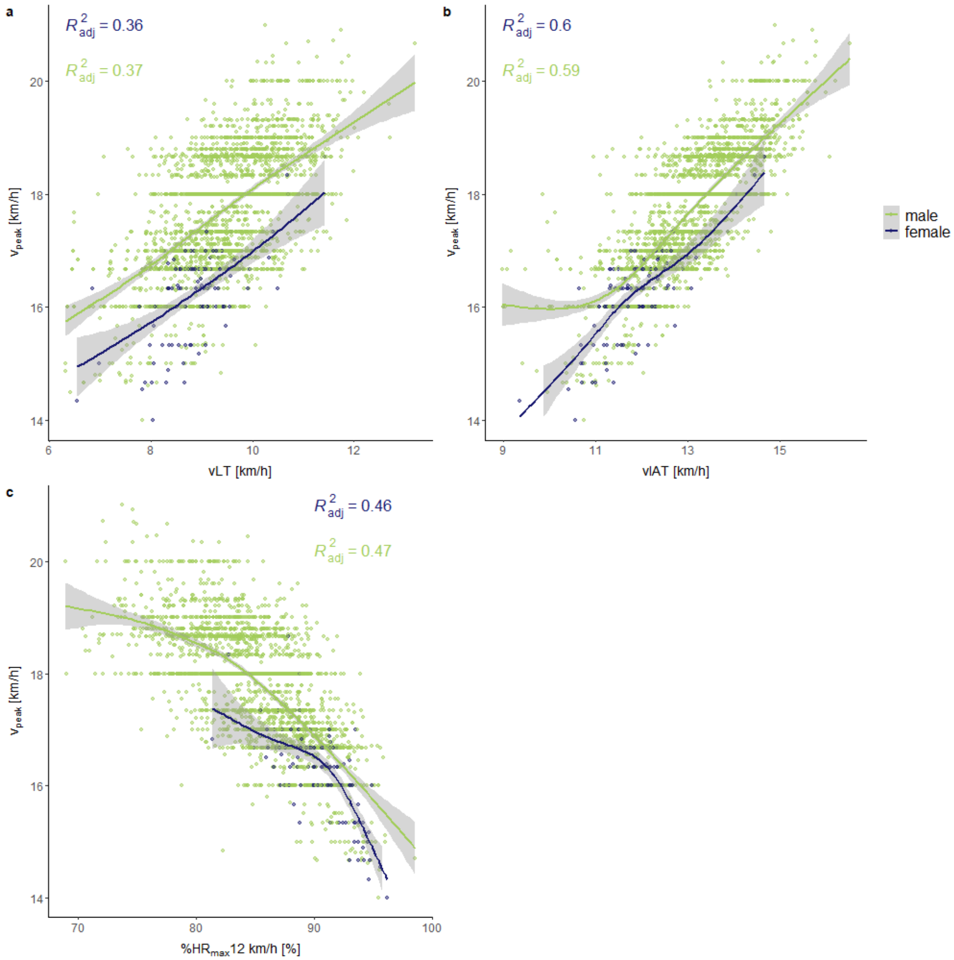
Statistical methods						
4. For continuous scores: Was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC) or Limits of Agreement (LoA) calculated?	NA	NA	3	NA	3	2
Other						
6. Were there any other important flaws in the design or statistical methods of the study?	NA	NA	3	NA	3	3
Box 8. Criterion validity						
Statistical methods						
1. For continuous scores: Were correlations, or the area under the receiver operating curve calculated?	3	0	3	3	3	0
Other						
3. Were there any other important flaws in the design or statistical methods of the study?	1	3	1	3	3	3
Box 9a. Convergent validity						
Design requirements						
1 Is it clear what the comparator instrument(s) measure(s)?	3	3	3	3	3	3
2 Were the measurement properties of the comparator instrument(s) sufficient?	3	3	3	3	3	3
Statistical methods						
3 Were design and statistical methods adequate for the hypotheses to be tested?	3	3	3	3	3	3

3 = very good; 2 = adequate; 1 = doubtful; 0 = inadequate, and NA = not applicable.

4 Paper IV Supplementary Table 1: Descriptives of included participants.

	Overall N = 2,648	**95% CI**	**male N = 2,524**	**95% CI**	**female N = 124**	**95% CI**
	n / N (%); mean (SD)					
Age [years]	18.6 (4.44)	18.4-19.7	18.4 (4.43)	18.2-18.6	22.1 (3.12)	21.6-22.7
Height [m]	176.1 (10.6)	175.7-176.5	176.31 (10.7)	175.9-176.7	170.9 (6.07)	169.8-171.9
Weight [kg]	70.5 (12.3)	70.0-70.9	70.8 (12.5)	70.2-71.3	64.4 (5.23)	63.4-65.3
Mode						
Field	1,073 (40%)	39%-42%	1,073 (43%)	41%-44%	0 (0%)	0%-4%
Treadmill	1,575 (60%)	58%-61%	1,451 (57%)	56%-59%	124 (100%)	96%-100%
vLT [km/h]	9.4 (0.98)	9.4-9.5	9.5 (0.98)	9.4-9.5	8.9 (0.74)	8.8-9.0
%vLT [%]	53.4 (4.44)	53.3-53.6	53.4 (4.47)	53.2-53.6	54.6 (3.58)	54.0-55.3
vIAT [km/h]	13.1 (1.05)	13.0-13.1	13.1 (1.04)	13.1-13.1	11.9 (0.78)	11.8-12.1
%vIAT [%]	73.9 (3.70)	73.7-74.0	73.9 (3.73)	73.78-74.0	73.5 (3.08)	72.9-74.0
vL2 [km/h]	11.5 (1.50)	11.4-11.5	11.5 (1.50)	11.5-11.6	10.4 (1.15)	10.1-10.6
%vL2 [%]	64.9 (6.58)	64.7-65.2	65.0 (6.60)	64.7-65.2	63.5 (5.83)	62.4-64.5
vL4[km/h]	14.2 (1.20)	14.1-14.2	14.3 (1.17)	14.2-14.3	12.9 (0.93)	12.7-13.0
%vL4 [%]	80.3 (4.11)	80.1-80.4	80.3 (4.11)	80.2-80.5	79.0 (3.83)	78.3-79.7
vpeak [km/h]	17.7 (1.09)	17.6-17.7	17.7 (1.06)	17.7-17.8	16.3 (0.76)	16.2-16.4
%theorHRmax12kmh	84.4 (5.15)	84.2-84.6	84.2 (5.10)	84.0-84.4	89.3 (3.55)	88.6-89.9
%HRmax12kmh	85.4 (4.66)	85.2-85.6	85.2 (4.60)	85.0-85.3	90.3 (2.71)	89.8-90.7

CI – 95% confidence interval; SD - standard deviation; vLT - speed at minimum lactate equivalent; %vLT/vIAT/vL2/vL4 - speed at threshold relative to vpeak; vIAT - speed at LT + 1.5 mmol/L; vL2/vL4 - speed at a lactation concentration of 2 and 4 mmol/L; vpeak - maximal speed at incremental treadmill or track running test;%theorHRmax12km/h - percentage of heart rate at 12 km/h of theoretical maximal heart rate, i.e. 220 - age; %HRmax12km/h - percentage of heart rate at 12 km/h of maximal heart rate.



5 Paper IV Supplementary Figure 1: Scatterplots with regression lines, 95% confidence interval (grey area), and adjusted R2 of the association between vpeak and vLT (a), vIAT (b), and %theorHRmax12km/h (c). Green lines represent regression lines for men and blue lines for women

6 Paper IV Supplementary Table 2: Models for the estimation of vpeak with age, squared age, and cubic age.

	Model 1 (N=2648)			Model 2 (N=2648)			Model 3 (N=2648)		
Predictors	**Estimates**	**95% CI**	**p**	**Estimates**	**95% CI**	**p**	**Estimates**	**95% CI**	**p**
(Intercept)	17.32	17.08 – 17.56	<0.001	15.56	13.83 – 15.29	<0.001	7.34	4.68 – 10.00	<0.001
age	0.01	0.00 – 0.03	0.027	0.29	0.22 – 0.36	<0.001	1.34	0.96 – 1.72	<0.001
age [2nd degree]				-0.01	-0.01 – -0.004	<0.001	-0.06	-0.07 – -0.04	<0.001
age [3rd degree]							0.007	0.0005 – 0.001	<0.001
Random Effects									
σ^2	0.34			0.33			0.33		
τ_{00}	0.90			0.89			0.89		
ICC	0.72			0.73			0.73		
N	889			889			889		
Marginal R^2 / Conditional R^2	0.00 / 0.73			0.02 / 0.74			0.03 / 0.74		
AIC	6411			6365			6353		
RMSE	0.50			0.49			0.49		
σ	0.59			0.58			0.57		

CI – 95% confidence interval; p – significance value (bold – $p<0.05$); σ^2 – sigma, i.e., residual variance; $\tau_{00\ id}$ – tau, i.e., random intercept variance; ICC = intra class correlation coefficient; N_{id} – number of IDs; marginal or conditional R^2 – coefficient of determination for fixed or random effects, respectively; AIC - Akaike information criterion; RMSE - root mean squared error, σ - residual standard deviation.

7 Paper IV Supplementary Table 3: Models for the estimation of vpeak with sex, cubic age, v2mmol, and v4mmol (model 4) and vLT and vIAT (model 5).

	Model 4 (N=2648)			Model 5 (N=2648)		
Predictors	**Estimates**	**95% CI**	**p**	**Estimates**	**95% CI**	**p**
(Intercept)	1.16310	-0.57 – 2.90	0.19	0.76163	-1.04 – 2.57	0.41
vL2	-0.27435	-0.32 – -0.23	<0.001			
vL4	0.96317	0.91 – 1.02	<0.001			
sex [female]	-0.57110	-0.73 – -0.41	<0.001	-0.75120	-0.92 – -0.59	<0.001
age [1st degree]	0.72898	0.49 – 0.97	<0.001	0.91284	0.66 – 1.16	<0.001
age [2nd degree]	-0.02748	-0.04 – -0.02	<0.001	-0.03467	-0.05 – -0.02	<0.001
age [3rd degree]	0.00032	0.0001 – 0.0005	<0.001	0.00042	0.0002 – 0.0006	<0.001
vLT				-0.17870	-0.22 – -0.13	<0.001
vIAT				0.85159	0.81 – 0.90	<0.001
Random Effects						
σ^2	0.21			0.22		
τ_{00}	0.17 $_{id}$			0.20 $_{id}$		
ICC	0.45			0.47		
N	889 $_{id}$			889 $_{id}$		
Marginal R^2 / Conditional R^2	0.65 / 0.81			0.62 / 0.80		
AIC	4411			4552		
RMSE	0.41			0.41		
σ	0.46			0.47		

CI – 95% confidence interval; p – significance value (bold – $p<0.05$); vLT - speed at minimum lactate equivalent; %vLT/vIAT/vL2/vL4 - speed at threshold relative to vpeak; vIAT - speed at LT + 1.5 mmol/L; σ^2 – sigma, i.e., residual variance; $\tau_{00\ id}$ – tau, i.e., random intercept variance; ICC = intra class correlation coefficient; N_{id} – number of IDs; marginal or conditional R^2 – coefficient of determination for fixed or random effects, respectively; AIC - Akaike information criterion; RMSE - root mean squared error, σ - residual standard deviation.

8 Paper V Supplementary Information 1: Additional Statistical Analysis

The participants were clustered using the ‘kmeans’ function in the ‘stats’ package (Team, 2022). Based on their ASR, the optimal number were two clusters (between sum of squares / total sum of squares = 77.0%) resulting in a high ASR (hASR) and a low ASR (lASR) group. For a comparison of the descriptive results between the two groups, independent Student’s t-Tests were calculated using the ‘t.test’ function (stats package) (Team, 2022). To detect possible differences between the two ASR groups regarding their acute responses to the HITT, i.e., biochemical, neuromuscular, cardiac, and athlete-reported variables, a two-way ANOVA (time*cluster) was conducted using the ‘contrast’ function in the ‘emmeans’ package (Searle et al., 1980). Posthoc comparisons were based on Bonferroni’s correction. The effect sizes (d) were calculated as Cohen's d with the ‘eff_size’ function in the ‘emmeans’ package (Searle et al., 1980). $0.2 \leq d < 0.5$ represent small, $0.5 \leq d < 0.8$ medium, and $d \geq 0.8$ represent large effects (Cohen, 1988). For all calculations, the significance level was set at $\alpha = 0.05$ and 95% confidence intervals (CI) were included.

9 Paper V Supplementary Information 2: Descriptive Results and HIIT Intensity

The participants were clustered into two groups, the hASR group (n=7; females n=2; middle distance runners n=1) and the lASR group (n=11; females n=5; middle distance runners n=11). The two groups did not show significant differences ($p > 0.05$; $0.07 \leq d \leq 0.64$) between the mean age, body mass, height, world athletics (WA) scores, and $\dot{V}O_2max$ (see Supplementary Table 1). However, the MAS (mean differences (MD)=1.85 km/h; $p < 0.05$; d=1.38) was significantly higher for the lASR group compared to the hASR group; while the MSS (MD=-2.48 km/h; $p < 0.05$; d=-1.18), the ASR (MD=-4.33; $p < 0.01$; d=-3.63), and the SRR (MD=-0.38; $p < 0.01$; d=-3.61) was lower for the lASR group than for the hASR group. The absolute intensity for the HIIT, i.e., 110% of MAS, and the relative portion of ASR (%ASR) for the intensity were both higher for the lASR group compared to the hASR group (MD=2.04 km/h; $p < 0.05$; d=1.39; MD=4.27%; $p < 0.05$; d=4.08; respectively). In contrast, t90%HRmax and t90%$\dot{V}O_2max$ during the HIIT were similar between the groups ($p > 0.05$; $0.02 \leq d \leq 0.42$).

10 Paper V Supplementary Table 1: Descriptive results.

	Age [years]	Mass [kg]	Height [m]	WA scores	$\dot{V}O_2max$ [mL/min/kg]	MAS [km/h]	MSS [km/h]	ASR [km/h]	SRR	110%MAS [km/h]	%ASR	T90% $\dot{V}O_2max$ [s]	T90% HRmax [s]
	Mean±SD												
High ASR (n=7)	15.57±0.53	60.0 ±8.0	1.75±0.09	803±99	54.00±4.60	15.04 ±1.42	33.18 ±1.88	18.15 ±1.06	2.15± 0.13	16.54±1.57	8.31± 0.90	31±39	1,044±170
Low ASR (n=11)	16.06±0.83	58.0 ±8.0	1.74±0.07	796±93	55.90±3.80	16.89 ±1.24 *	30.70 ±2.31 *	13.82 ±1.32 **	1.77± 0.06**	18.58±1.37*	12.28 ±1.04 **	50±50	1,048±119
Total (N=18)	15.89±0.76	59.0 ±8.0	1.75±0.08	799±92	55.20±4.10	16.17 ±1.58	31.67 ±2.44	15.50 ±2.48	1.91± 0.21	17.78±1.73	10.74 ±2.22	43±46	1,046±136

MAS – maximal aerobic speed; MSS – maximal sprinting speed; ASR – anaerobic speed reserve; SRR – speed reserve ratio; $\dot{V}O_2max$ – relative maximal oxygen update; %ASR – 110%MAS, i.e., intensity of high-intensity interval training (HIIT), relative to ASR; T90% $\dot{V}O_2max$ – time spent above 90% of $\dot{V}O_2max$ during HIIT, T90% HRmax – time spent above 90% of HRmax during HIIT; SD – standard deviation; * indicates $p<0.05$; ** indicates $p<0.001$.

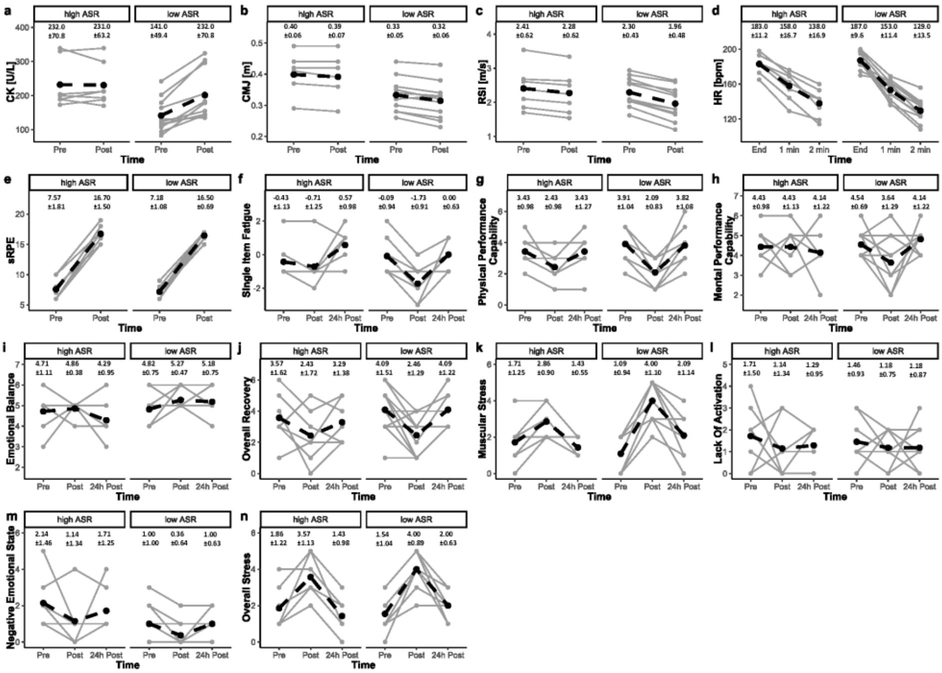
11 Paper V Supplementary Information 3: ANOVA Results for Biochemical, Neuromuscular, and Cardiac Response

The CK showed a significant increase from pre to post HIIT only for the lASR group (MD=59.73 U/L; $p=0.04$; $d=0.97$; see Supplementary Table 2 and Supplementary Figure 1). The pre/post HIIT changes in CMJ height ($p\geq0.48$; $-0.32\leq d\leq0.11$) and the RSI ($p\geq0.15$; $-0.73\leq d\leq-0.22$) were not significantly different for both groups. The HR decreased significantly for both groups from the end of HIIT to one-minute post ($-33.91\leq MD\leq-25.14$ bpm; $p<0.01$; $-3.22\leq d\leq-1.76$) and from one minute to two minutes post HIIT ($-23.82\leq MD\leq-20.00$ bpm; $p\leq0.02$; $-1.91\leq d\leq-1.19$). No significant interaction effects, i.e., a difference between the time difference and group difference, were found ($p\geq0.33$; $-0.67\leq d\leq-0.18$) but a large effect for CK ($p=0.17$; $d=0.96$).

12 Paper V Supplementary Table 2: ANOVA results for the biochemical, neuromuscular, and cardiac variables.

		T2 vs. T1				Low ASR vs. High ASR			Time Difference vs. Group Difference		
		MD (95% CI)	p	d (95% CI)		MD (95% CI)	p	d (95% CI)	MD (95% CI)	p	d (95% CI)
CK [U/L]	High ASR:	-1.43 (-70.9–68.10)	0.97	-0.02 (-1.23–1.26)	Pre	90.64 (27.80–153.00)	<0.01	1.49 (0.75–2.80)	61.16 (-27.70–150.00)	0.17	0.96 (-0.46–2.37)
	Low ASR:	59.73 (4.29–115.00)	0.04	0.97 (0.15–1,84)	Post	29.48± (-33.40–92.30)	0.35	0.44 (-0.46–1.59)			
CMJ [m]	High ASR:	-0.01 (-0.07–0.06)	0.82	-0.11 (-1.41–1.06)	Pre	-0.07 (-0.13–-0.01)	0.03	-1.12 (-2.82–-0.17)	-0.01 (-0.09–0.07)	0.79	-0.18 (-1.58–1.21)
	Low ASR:	-0.02 (-0.07–0.03)	0.48	-0.32 (-1.33–0.51)	Post	-0.08 (-0.14–-0.02)	0.01	-1.22 (-2.82–-0.23)			
RSI [m/s]	High ASR:	-0.13 (-0.70–0.43)	0.63	-0.22 (-1.54–0.93)	Pre	-0.12 (-0.63–0.40)	0.65	-0.22 (-1.21–0.77)	-0.20 (-0.93–0.53)	0.58	-0.38 (-1.77–1.02)
	Low ASR:	-0.33 (-0.79–0.12)	0.15	-0.73 (-1.87–0.13)	Post	-0.31 (-0.83–0.20)	0.22	-0.60 (-1.60–0.40)			
HRR 1' [bpm]	High ASR:	-25.14 (-39.20–-11.10)	<0.01	-1.76 (-3.61–-0.94)	End	4.18 (-8.52–16.90)	0.51	0.40 (-0.68–1.65)	-8.77 (-26.70–9.20)	0.33	-0.67 (-2.05–0.71)
	Low ASR:	-33.91 (-45.10–-22.70)	<0.01	-3.22 (-4.94–-2.44)	1min	-4.58 (-17.30–8.12)	0.47	-0.32 (-1.84–0.67)			
HRR 2' [bpm]	High ASR:	-20.00 (-34.00–-5.96)	0.02	-1.19 (-3.00–-0.17)	2min	-8.40 (-21.10–4.30)	0.19	0.55 (-2.12–0.50)	-3.82 (-21.80–14.15)	0.67	-0.29 (-1.67–1.08)
	Low ASR:	-23.82 (-35.00–-12.60)	<0.01	-1.91 (-3.41–-1.05)							

CK – Creatine kinase; CMJ – Countermovement jump height; RSI – Reactive strength index; HRR1' – Heart rate recovery from end of HIIT to 1 min post; HR2' – Heart rate recovery from 1 min post to 2 min post HIIT; T1 – Pre for CK, CMJ, and RSI, end of HIIT for ΔHR1', and 1 min post for HR2'; T2 – Post for CK, CMJ, and RSI, 1 min post for HR1', and 2 min post for HR2'; ASR – Anaerobic speed reserve; MD – Mean difference; d – Cohen's d, i.e., effect size; 95% CI – 95% confidence interval; vs. – Versus



13 Paper V Supplementary Figure 1: Spaghetti plots for the pre-post (and 24 h post) comparisons for the objective and subjective variables divided into the high ASR and low ASR groups including mean values ± standard deviation. ASR – Anaerobic Speed Reserve; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion.

14 Paper V Supplementary Information 4: ANOVA Results for Athlete-Reported Measures.

The single item for fatigue, Physical Performance Capacity, Overall Recovery, and Muscular Stress showed significant differences from pre to post only for the lASR group ($-1.82 \leq MD \leq 2.94$; $p \leq 0.03$; $-1.93 \leq d \leq 2.89$; see Supplementary Figure 1 and Supplementary Table 3). However, the single item for fatigue, Physical Performance Capacity, Overall Recovery, and Muscular Stress changed significantly from post to 24 h post for the lASR group to a similar level as pre HIIT ($-1.91 \leq MD \leq 1.73$; $p \leq 0.03$; $-1.87 \leq d \leq 2.21$). The Overall Stress increased significantly for both groups from pre to post ($1.71 \leq MD \leq 2.45$; $p \leq 0.01$; $1.77 \leq d \leq 2.54$) but decreased again for both groups from post to 24 h post ($-2.14 \leq MD$-2.00; $p < 0.01$; $-2.21 \leq d \leq -2.07$). The sRPE increased significantly for both groups from pre to post ($9.14 \leq MD \leq 9.27$; $p < 0.01$, $7.35 \leq d \leq 7.46$). Significant interaction effects were found for the single item for fatigue pre-post HIIT, for the Mental Performance Capacity post-24 h post HIIT, and the Muscular Stress pre-post HIIT ($-1.35 \leq MD \leq 1.77$; $p \leq 0.04$; $-1.41 \leq d \leq 1.73$).

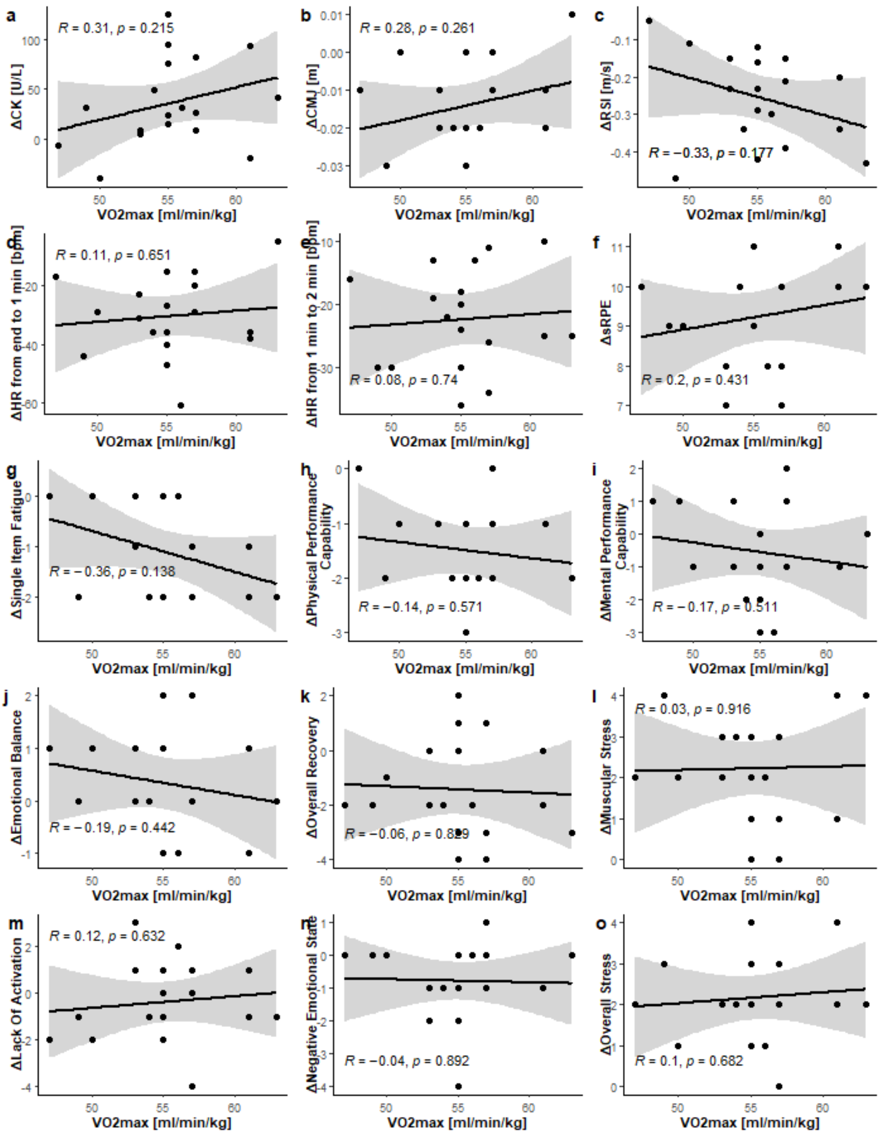
15 Paper V Supplementary Table 3: ANOVA results for the athlete-reported variables.

		Post vs. Pre			24h Post vs. Post				Low ASR vs. High ASR				Time Difference vs. Group (Low vs. High ASR) Difference		
		MD (95% CI)	p	d (95% CI)	MD (95% CI)	p	d (95% CI)		MD (95% CI)	p	d (95% CI)		MD (95% CI)	p	d (95% CI)
sRPE	High ASR:	9.14 (7.79–10.50)	<0.01	7.35 (5.19–9.52)	-	-	-	Pre	-0.39 (-1.61–0.84)	0.52	-0.31 (-1.30–0.68)	Post vs. Pre	0.13 (-1.60–1.86)	0.88	0.10 (-1.29–1.50)
	Low ASR:	9.27 (8.19–10.40)	<0.01	7.46 (5.37–9.54)	-	-	-	Post	-0.26 (-1.48–0.97)	0.67	-0.21 (-1.20–0.78)				
Single Item Fatigue	High ASR:	-0.29 (-1.31–0.74)	1.00	-0.24 (-1.44–0.84)	1.29 (0.26–2.31)	0.04	1.14 (0.03–4.56)	Pre	0.34 (-0.59–1.27)	0.47	0.32 (-0.65–1.90)	Post vs. Pre	-1.35 (-2.67–-0.04)	0.04	-1.41 (-2.82–-0.01)
	Low ASR:	-1.64 (-2.46–-0.82)	<0.01	-1.77 (-3.11–-1.03)	1.73 (0.91–2.55)	<0.01	2.21 (1.34–4.03)	Post	-1.01 (-2.19–-1.94)	0.03	-0.93 (-2.09–-0.11)	24h Post vs. Post	0.44 (-0.87–1.76)	0.50	0.46 (-0.92–1.84)
								24h Post	-0.57 (-1.50–0.08)	0.22	-0.70 (-2.19–0.38)				
Physical Performance Capability	High ASR:	-1.00 (-2.10–0.10)	0.22	-1.02 (-2.73–0.00)	1.00 (-0.10–2.10)	0.22	0.88 (-0.14–3.15)	Pre	0.48 (-0.52–1.48)	0.34	0.48 (-0.52–1.67)	Post vs. Pre	-0.82 (-2.23–0.59)	0.25	-0.79 (-2.18–0.59)
	Low ASR:	-1.82 (-2.70–-0.94)	<0.01	-1.93 (-3.49–-1.17)	1.73 (0.85–2.61)	<0.01	1.79 (1.12–3.06)	Post	-0.34 (-1.34–0.66)	0.50	-0.37 (-1.57–0.74)	24h Post vs. Post	0.73 (-0.68–2.14)	0.31	0.71 (-0.67–2.01)
								24h Post	0.39 (-0.61–1.39	0.44	0.33 (-0.82–1.37)				
Mental Performance Capability	High ASR:	0.00 (-1.07–1.07	1.00	0.00 (-1.15–1.47)	-0.29 (-1.35–0.78)	1.00	-0.24 (-1.59 – 1.02)	Pre	0.12 (-0.85–1.08)	0.81	0.14 (-0.97–1.40)	Post vs. Pre	-0.91 (-2.27–0.45)	0.19	-0.92 (-2.30–0.47)
	Low ASR:	-0.91 (-1.76–-0.06)	0.11	-0.88 (-2.40–-0.06)	1.18 (0.33–2.03)	0.02	1.18 (0.34 – 2.86)	Post	-0.79 (-1.76 – 0.17)	0.10	-0.65 (-2.04–0.29)	24h Post vs. Post	1.47 (0.10–2.83)	0.04	1.48 (0.07–2.89)
								24h Post	0.68 (-0.29–1.64)	0.17	0.70 (-0.23–2.18)				

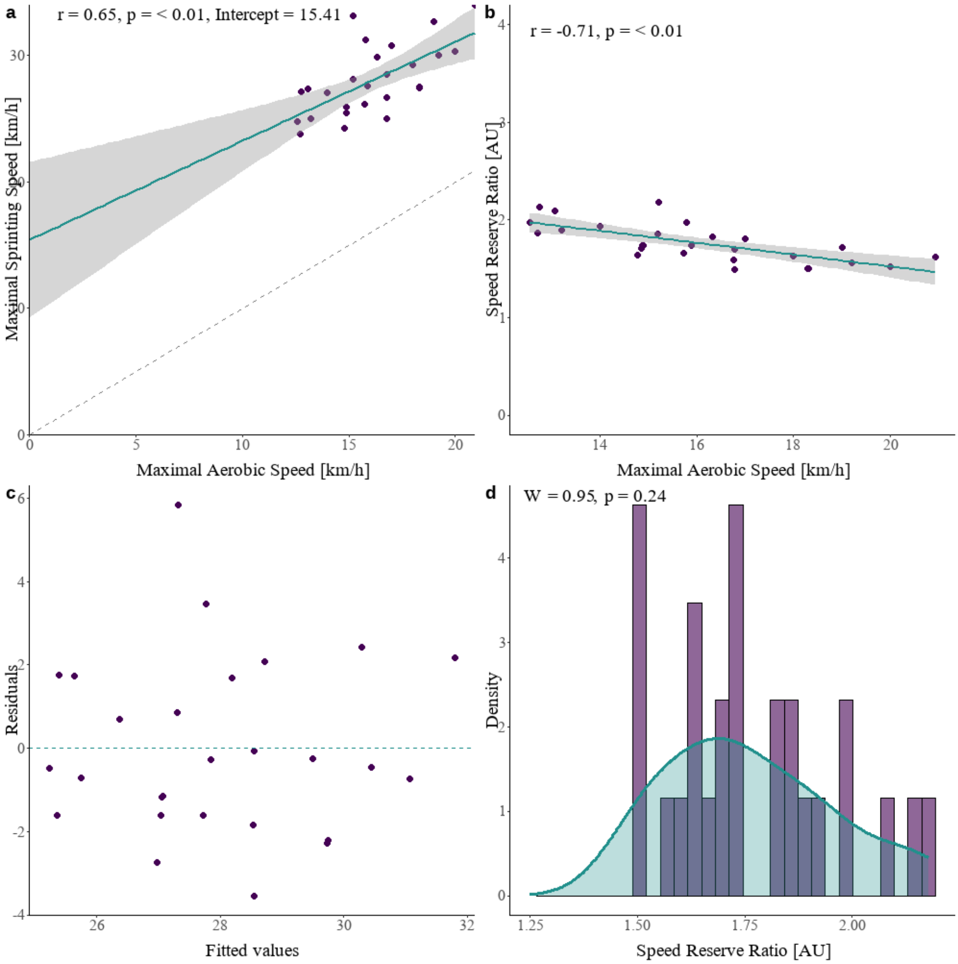
Emotional Balance	High ASR:	0.14 (-0.86–1.14)	1.00	0.19 (-0.89–1.27)	-0.57 (-1.57–0.43)	0.49	-0.76 (-1.85–0.33)	Pre	0.10 (-0.63–0.84)	0.78	0.14 (-0.83–1.11)	Post vs. Pre	0.31 (-0.72–1.35)	0.55	0.41 (-0.96–1.79)
	Low ASR:	0.45 (-0.34–1.25)	0.49	0.60 (-0.26–1.47)	-0.09 (-0.89–0.71)	1.00	-0.12 ‘ (-0.98–0.74)	Post	0.42 (-0.36–1.15)	0.26	0.55 (-0.43–1.53)	24h Post vs. Post	0.48 (-0.55–1.51)	0.35	0.64 (-0.74–2.02)
								24h Post	0.90 (0.17–1.63)	0.02	1.19 (0.19–2.19)				
Overall Recovery	High ASR:	-1.14 (-3.05–0.77)	0.43	-0.79 (-1.88–0.29)	0.86 (-1.05–2.77)	0.81	0.60 (-0.49–1.68)	Pre	0.52 (-0.88–1.92)	0.46	0.36 (-0.61–1.34)	Post vs. Pre	-0.49 (-2.47–1.48)	0.62	-0.34 (-1.72–1.03)
	Low ASR:	-1.64 (-3.16–-0.11)	0.03	-1.14 (-2.03–-0.25)	1.64 (0.11–3.16)	0.03	1.14 (0.25–2.03)	Post	0.03 (-1.37–1.42)	0.97	0.02 (-0.95–0.99)	24h Post vs. Post	0.78 (-1.20–2.76)	0.43	0.54 (-0.84–1.92)
								24h Post	0.81 (-0.59–2.20)	0.25	0.56 (-0.42–1.54)				
Muscular Stress	High ASR:	1.14 (-0.21–2.49)	0.12	1.12 (0.02–2.22)	-1.43 (-2.77–-0.08)	0.03	-1.40 (-2.51–-0.29)	Pre	-0.62 (-1.61–0.40)	0.21	-0.61 (-1.59–0.40)	Post vs. Pre	1.77 (0.37–3.17)	0.01	1.73 (0.31–3.15)
	Low ASR:	2.91 (1.83–3.99)	<0.01	2.86 (1.82–3.89)	-1.91 (-2.99–-0.83)	<0.01	-1.87 (-2.81–-0.93)	Post	1.14 (0.15–2.13)	0.02	1.12 (0.12–2.12)	24h Post vs. Post	-0.48 (-1.88–0.92)	0.49	-0.47 (-1.85–0.91)
								24h Post	0.66 (-0.33–1.65)	0.19	0.65 (-0.33–1.63)				
Lack of Activation	High ASR:	-0.57 (-1.95–0.81)	0.92	-0.55 (-1.63–0.53)	0.14 (-1.23–1.52)	1.00	0.14 (-0.94–1.21)	Pre	-0.26 (-1.27–0.75)	0.61	-0.25 (-1.22–0.72)	Post vs. Pre	0.30 (-1.13–1.73)	0.68	0.29 (-1.09–1.66)
	Low ASR:	-0.27 (-1.37–0.83)	1.00	-0.26 (-1.12–0.60)	0.00 (-1.10–1.10)	1.00	0.00 (-0.86–0.86)	Post	0.04 (-0.97–1.05)	0.94	0.04 (-0.94–1.01)	24h Post vs. Post	-0.14 (-1.57–1.28)	0.84	-0.14 (-1.51 – 1.24)
								24h Post	-0.10 (-1.11–0.91)	0.84	-0.10 (-1.07–0.87)				

Negative Emotional State	**High ASR:**	**-1.00 (-2.38–0.38)**	**0.23**	**-0.96 (-2.06–0.13)**	**0.57 (-0.81–1.95)**	**0.92**	**0.55 (-0.53–1.63)**	**Pre**	**-1.14 (-2.15–-0.13)**	**0.03**	**-1.10 (-2.10–-0.10)**	**Post vs. Pre**	**0.36 (-1.06–1.79)**	**0.61**	**0.35 (-1.03–1.73)**
	Low ASR:	-0.64 (-1.73–0.46)	0.47	-0.61 (-1.48–0.25)	0.64 (-0.46–1.73)	0.47	0.61 (-0.25–1.48)	Post	-0.78 (-1.79–0.23)	0.13	-0.75 (-1.74–0.23)	24h Post vs. Post	0.06 (-1.36–1.49)	0.93	0.06 (-1.31–1.44)
								24h Post	-0.71 (-1.72–0.30)	0.16	-0.69 (-1.67–0.29)				
Overall Stress	High ASR:	1.71 (0.43–2.99)	0.01	1.77 (0.64–2.91)	-2.14 (-3.43–-0.86)	<0.01	-2.21 (-3.38–-1.05)	Pre	-0.31 (-1.25–0.63)	0.51	-0.32 (-1.29–0.65)	Post vs. Pre	0.74 (-0.59–2.07)	0.27	0.76 (-0.62–2.15)
	Low ASR:	2.45 (1.43–3.48)	<0.01	2.54 (1-53–3.54)	-2.00 (-3.02–-0.98)	<0.01	-2.07 (-3.02–-1.11)	Post	0.43 (-0.51–1.37)	0.36	0.44 (-0.53–1.42)	24h Post vs. Post	0.14 (-1.19–0.47)	0.83	0.15 (-1.23–1.52)
								24h Post	0.57 (-0.37–1.51)	0.23	0.59 (-0.39–1.57)				

sRPE – Session ratings of perceived exertion; ASR – Anaerobic speed reserve; MD – Mean difference; d – Cohen's d, i.e., effect size; 95% CI – 95% confidence interval; vs. - Versus.



16 Paper V Supplementary Figure 2: Scatterplots with regression lines and 95% confidence intervals (grey area) for $\dot{V}O_2max$ with the different objective and athlete-reported variables. $\dot{V}O_2max$ – Maximal oxygen consumption; Δ – Delta, i.e., pre-post difference; CK – Creatine kinase; CMJ – Countermovement-Jump; RSI – Reactive Strength Index; HR – Heart rate; sRPE – Session Ratings of Perceived Exertion; r – Pearson's r; p – significance value.



17 Paper VI Supplementary Figure 1: Assumption check for the calculation of the ratio maximal sprinting speed (MSS) divided by maximal aerobic speed (MAS). a. Regression line of MAS and MSS should intersect with the origin and linearity should be given. Dashed line represents line of origin. b. Regression line of the ratio and MAS should be parallel to the x-axis. c. Linearity between MAS and MSS, i.e. residuals of linear model should be randomly scattered. d. Distribution of SRR should be normal (Van Hooren et al., 2023).

18 Paper VI Supplementary Table 1: Results of linear mixed model analyses for the comparison of pre- to post-tests of HIIT versus SIT with Bonferroni post-hoc analyses.

	Time x Group + (1 | ID)						**post hoc (contrasts)**										
								T2 vs. T1				SIT vs. HIIT			Time Difference vs. Group Difference		
		beta	95% CI	p	ICC	marginal R2/ conditional R2		MD (95% CI)	p	d (95% CI)		MD (95% CI)	p	d (95% CI)	MD (95% CI)	p	d (95% CI)
MAS [km/h]	Intercept	15.68	14.40 – 16.95	<0.001	0.88	0.04/0.89	HIIT	0.79 (0.16–1.42)	0.02	1.01 (0.18–1.84)	Pre	0.69 (-1.2–2.50)	0.44	0.88 (-1.44–3.20)	-0.11 (-0.98–0.77)	0.81	-0.14 (-1.25–0.98)
	Group (SIT)	0.69	-1.09 – 2.46	0.44													
	Time (post)	0.79	0.17 – 1.41	0.01			SIT	0.68 (0.07–1.29)	0.03	0.87 (0.08–1.67)	Post	0.58 (-1.22–2.39)	0.51	0.75 (-1.57–3.06)			
	Group (SIT) × Time (post)	-0.11	-0.96 – 0.75	0.81													
MSS [km/h]	Intercept	27.83	26.25 – 29.40	<0.001	0.98	0.03/0.98	HIIT	-0.11 (-0.42–0.19)	0.45	-0.30 (-1.11–0.51)	Pre	0.26 (-1.98–2.50)	0.81	0.70 (-5.30–6.69)	0.93 (0.51–1.35)	<0.001	2.48 (1.25–3.72)
	Group (SIT)	0.26	-1.93 – 2.45	0.812													
	Time (post)	-0.11	-0.41 – 0.18	0.444			SIT	0.82 (0.52–1.11)	<0.001	2.18 (1.28–3.08)	Post	1.19 (-1.05–3.43)	0.28	3.18 (-2.85–9.21)			
	Group (SIT) × Time (post)	0.93	0.52 – 1.34	<0.001													

ASR [km/h]	Inter-cept	12.15	11.03 – 13.27	<0.001	0.82	0.03/0.83	HIIT	-0.90 (-1.59–-0.22)	0.01	-0.81 (-1.90–-0.24)	Pre	-0.43 (-2.01–1.15)	0.58	-0.51 (-2.38–1.36)	1.03 (0.09–1.98)	0.03	1.22 (0.08–2.36)
	Group (SIT)	-0.43	-1.98 – 1.13	0.582													
	Time (post)	-0.90	-1.57 – -0.23	0.009			SIT	0.13 (-0.53–0.79)	0.68	0.16 (-0.62–0.93)	Post	0.61 (-0.97–2.18)	0.44	0.72 (-1.16–2.59)			
	Group (SIT) × Time (post)	1.03	0.11 – 1.96	0.029													
SRR [AU]	Inter-cept	Jan 79	1.69 – 1.89	<0.001	0.71	0.04/0.73	HIIT	-0.10 (-0.18–-0.03)	0.01	-1.08 (-1.91–-0.25)	Pre	-0.06 (-0.19–0.08)	0.43	-0.58 (-2.05–0.89)	0.08 (-0.03–0.19)	0.13	0.85 (-0.28–1.97)
	Group (SIT)	-0.05	-0.19 – 0.08	0.425													
	Time (post)	-0.10	-0.18 – -0.03	0.008			SIT	-0.02(-0.10–0.05)	0.54	-0.24 (-1.01–0.54)	Post	0.03 (-0.11–0.16)	0.71	0.27 (-1.20–1.74)			
	Group (SIT) × Time (post)	0.08	-0.02 – 0.18	0.126													
t40 [s]	Inter-cept	5.93	5.66 – 6.20	<0.001	0.97	0.03/0.97	HIIT	0.03 (-0.04–0.09)	0.40	0.34 (-0.47–1.15)	Pre	-0.12 (-0.50–0.27)	0.54	-1.41 (-16.10–3.28)	-0.10 (-0.19–-0.01)	0.04	-1.17 (-2.32–-0.03)
	Group (SIT)	-0.11	-0.49 – 0.26	0.539													
	Time (post)	0.03	-0.04 – 0.09	0.391			SIT	-0.07 (-0.13–0.01)	0.04	-0.84 (-1.63–-0.04)	Post	-0.21 (-0.59–0.17)	0.27	-2.58 (-7.29–2.13)			
	Group (SIT) × Time (post)	-0.10	-0.18 – -0.01	0.036													
AeSR [km/h]	Inter-cept	2.98	2.10 – 3.85	<0.001	0.74	0.07/0.76	HIIT	0.40 (-0.24–1.03)	0.21	0.51 (-0.30–1.31)	Pre	0.01 (-1.22–1.24)	0.99	0.01 (-1.56–1.59)	0.21 (-0.67–1.09)	0.63	0.27 (-0.85–1.38)
	Group (SIT)	0.01	-1.20 – 1.22	0.986													
	Time (post)	0.40	-0.22 – 1.01	0.203			SIT	0.60 (-0.00–1.21)	0.05	0.77 (-0.01–1.56)	Post	0.22 (-1.01–1.45)	0.72	0.28 (-1.29–1.85)			
	Group (SIT) × Time (post)	0.21	-0.65 – 1.06	0.627													

relV̇O₂max [mL/min/kg]	Intercept	53.23	49.31 – 57.15	<0.001	0.91	0.05/0.92	HIIT	0.46 (-1.23–2.16)	0.58	0.22 (-0.59–1.03)	Pre	2.95 (-2.61–8.50)	0.29	1.40 (-1.26–4.07)	0.15 (-2.21–2.50)	0.90	0.07 (-1.05–1.19)
	Group (SIT)	2.95	-2.50 – 8.39	0.282													
	Time (post)	0.46	-1.19 – 2.12	0.578			SIT	0.61 (-1.02–2.24)	0.45	0.29 (-0.49–1.07)	Post	3.09 (-2.46–8.65)	0.26	1.47 (-1.19–4.14)			
	Group (SIT) × Time (post)	0.15	-2.15 – 2.45	0.898													
V̇O₂max [L/min]	Intercept	3.66	3.19 – 4.13	<0.001	0.97	0.01/0.97	HIIT	0.06 (-0.10–0.14)	0.72	0.14 (-0.67–0.95)	Pre	0.17 (-0.50–0.84)	0.61	1.18 (-3.53–5.90)	0.00 (-0.16–0.16)	0.96	0.03 (-1.10–1.15)
	Group (SIT)	0.17	-0.49 – 0.82	0.608													
	Time (post)	0.02	-0.09 – 0.13	0.722			SIT	0.02 (-0.09–0.14)	0.67	0.17 (-0.61–0.4)	Post	0.17 (-0.50–0.84)	0.60	1.21 (-3.51–5.92)			
	Group (SIT) × Time (post)	0.00	-0.15 – 0.16	0.964													
vLT [km/h]	Intercept	9.49	8.93 – 10.05	<0.001	0.89	0.09/0.91	HIIT	0.23 (-0.03–0.49)	0.08	0.71 (-0.11–1.52)	Pre	0.67 (-0.13–1.46)	0.10	2.04 (-0.43–4.51)	-0.10 (-0.47–0.26)	0.57	-0.31 (-1.43–0.81)
	Group (SIT)	0.66	-0.11 – 1.44	0.093													
	Time (post)	0.23	-0.03 – 0.49	0.077			SIT	0.13 (-0.13–0.38)	0.31	0.39 (-0.39–1.17)	Post	0.56 (-0.23–1.36)	0.16	1.73 (-0.74–4.19)			
	Group (SIT) × Time (post)	-0.1	-0.46 – 0.25	0.568													
vIAT [km/h]	Intercept	12.7	11.96 – 13.44	<0.001	0.95	0.05/0.96	HIIT	0.39 (0.16–0.62)	0.002	1.38 (0.52–2.23)	Pre	0.68 (-0.38–1.73)	0.20	2.38 (-1.36–6.13)	-0.31 (-0.63–0.01)	0.05	-1.10 (-2.24–0.04)
	Group (SIT)	0.68	-0.35 – 1.71	0.193													
	Time (post)	0.39	0.17 – 0.62	0.001			SIT	0.08 (-0.14–0.30)	0.47	0.96 (-0.16–1.76)	Post	0.37 (-0.69–1.42)	0.48	1.28 (-2.44–5.00)			
	Group (SIT) × Time (post)	-0.31	-0.63 – -0.00	0.049													

v2mmol [km/h]	Inter-cept	11.60	10.33 – 12.87	<0.001	0.74	0.07/0.76	HIIT	0.66 (-0.29–1.61)	0.16	0.61 (-0.27–1.49)	Pre	-0.82 (-2.59–0.95)	0.35	-0.76 (-2.41–0.89)	0.59 (-0.73–1.91)	0.36	0.55 (-0.66–1.76)
	Group (SIT)	-0.82	-2.57 – 0.93	0.349													
	Time (post)	0.66	-0.26 – 1.59	0.156			SIT	1.26 (0.34–2.17)	0.009	1.16 (0.29–2.03)	Post	-0.23 (-1.99–1.54)	0.8	-0.21 (-1.85–1.43)			
	Group (SIT) × Time (post)	0.59	-0.69 – 1.87	0.355													
v3mmol [km/h]	Inter-cept	12.72	11.69 – 13.74	<0.001	0.93	0.02/0.93	HIIT	0.59 (0.19–1.00)	0.006	1.18 (0.34–2.02)	Pre	0.18 (-1.27–1.64)	0.80	0.37 (-2.53–3.26)	-0.27 (-0.83–0.29)	0.33	-0.54 (-1.66–0.58)
	Group (SIT)	0.18	-1.24 – 1.61	0.795													
	Time (post)	0.59	0.20 – 0.99	0.004			SIT	0.32 (-0.07–0.71)	0.103	0.64 (-0.15–1.43)	Post	-0.09 (-1.54–1.37)	0.9	-0.17 (-3.07–2.72)			
	Group (SIT) × Time (post)	-0.27	-0.82 – 0.28	0.327													
v4mmol [km/h]	Inter-cept	13.67	12.69 – 14.64	<0.001	0.95	0.01/0.95	HIIT	0.47 (0.14–0.80)	0.007	1.15 (0.31–1.99)	Pre	0.36 (-1.02–1.74)	0.60	0.88 (-2.51–4.27)	-0.28 (-0.74–0.18)	0.23	-0.68 (-1.80–0.45)
	Group (SIT)	0.36	-0.99 – 1.71	0.596													
	Time (post)	0.47	0.15 – 0.79	0.005			SIT	0.19 (-0.13–0.51)	0.224	0.47 (-0.31–1.25)	Post	0.08 (-1.30–1.47)	0.9	0.20 (-3.18–3.59)			
	Group (SIT) × Time (post)	-0.28	-0.72 – 0.17	0.221													
vpeak [km/h]	Inter-cept	17.51	16.58 – 18.45	<0.001	0.94	0.09/0.94	HIIT	0.49 (-0.14–0.83)	0.007	1.15 (0.31–1.99)	Pre	1.01 (-0.32–2.33)	0.13	2.38 (-0.78–5.54)	-0.08 (-0.56–0.40)	0.73	-0.19 (-1.31–0.93)
	Group (SIT)	1.01	-0.29 – 2.30	0.124													
	Time (post)	0.49	0.15 – 0.82	0.005			SIT	0.41 (-0.08–0.74)	0.02	0.84 (-0.52–1.00)	Post	0.93 (-0.40–2.25)	0.16	2.19 (-0.97–5.35)			
	Group (SIT) × Time (post)	-0.08	-0.54 – 0.38	0.731													

RE [mL/kg/km]	Inter-cept	209.25	197.63 – 220.88	<0.001	0.70	0.03/0.71	HIIT	-6.56 (-15.90–2.73)	0.16	-0.57 (-1.38–0.24)	Pre	3.53 (-12.80–19.90)	0.66	0.31 (-1.11–1.73)	0.21 (-12.70–13.10)	0.97	0.02 (-1.09–1.13)
	Group (SIT)	3.53	-12.61 – 19.68	0.662													
	Time (post)	-6.56	-15.63 – 2.51	0.152			SIT	-6.36 (-15.30–2.49)	0.16	-0.55 (-1.33–0.22)	Post	3.74 (-12.60–20.10)	0.64	0.33 (-1.10–1.75)			
	Group (SIT) × Time (post)	0.21	-12.39 – 12.80	0.974													

19 Paper VI Supplementary Table 2: Results of moderator analyses with MAS and MSS as well as SRR as moderators with locomotor variables.

	Group x pre-MAS + Group x pre-MSS					Group x pre-SRR				
		beta	95% CI	p	R^2/adj. R^2		beta	95% CI	p	R^2/adj. R^2
%ΔMAS	Group (SIT)	-5.93	-16.03 – 4.17	0.236	0.44/0.30	Group (SIT)	3.95	-4.52 – 12.42	0.345	0.44/0.37
	MAS	-3.57	-6.05 – -1.09	0.007		SRR	32.24	13.95 – 50.52	0.001	
	MSS	0.98	-0.56 – 2.52	0.201						
	Group (SIT) × MAS	0.95	-2.64 – 4.55	0.586		Group (SIT) × SRR	-14.21	-39.43 – 11.02	0.256	
	Group (SIT) × MSS	0.94	-1.39 – 3.27	0.41						
%ΔMSS	Group (SIT)	6.46	3.47 – 9.45	<0.001	0.61/0.52	Group (SIT)	5.22	2.33 – 8.12	0.001	0.48/0.41
	MAS	-0.16	-0.89 – 0.58	0.661		SRR	3.31	-2.94 – 9.56	0.284	
	MSS	0.22	-0.24 – 0.67	0.338						
	Group (SIT) × MAS	0.01	-1.06 – 1.07	0.992		Group (SIT) × SRR	-6.44	-15.07 – 2.18	0.136	
	Group (SIT) × MSS	-0.85	-1.54 – -0.16	0.018						
%ΔSR	Group (SIT)	22.39	10.89 – 33.90	0.001	0.60/0.50	Group (SIT)	10.54	-1.01 – 22.09	0.072	0.43/0.35
	MAS	2.6	-0.23 – 5.42	0.069		SRR	-19.03	-43.97 – 5.90	0.128	
	MSS	-0.01	-1.77 – 1.74	0.987						
	Group (SIT) × MAS	-0.13	-4.22 – 3.96	0.948		Group (SIT) × SRR	-8.27	-42.67 – 26.13	0.624	
	Group (SIT) × MSS	-3.73	-6.38 – -1.07	0.008						
%ΔSRR	Group (SIT)	0.2	0.04 – 0.36	0.015	0.57/0.47	Group (SIT)	0.01	-0.14 – 0.16	0.859	0.47/0.40
	MAS	0.06	0.02 – 0.10	0.002		SRR	-0.51	-0.83 – -0.19	0.003	
	MSS	-0.03	-0.06 – -0.00	0.024						
	Group (SIT) × MAS	-0.02	-0.07 – 0.02	0.294		Group (SIT) × SRR	0.16	-0.29 – 0.60	0.469	
	Group (SIT) × MSS	-0.01	-0.05 – 0.02	0.456						

%Δt40	Group (SIT)	-2.59	-5.59 – 0.42	0.088	0.32/0.15	Group (SIT)	-3.32	-5.91 – -0.72	0.014	0.28/0.19
	MAS	0.52	-0.22 – 1.26	0.156		SRR	-5.2	-10.79 – 0.39	0.067	
	MSS	-0.14	-0.60 – 0.32	0.532						
	Group (SIT) × MAS	-0.22	-1.29 – 0.85	0.675		Group (SIT) × SRR	5.7	-2.02 – 13.42	0.14	
	Group (SIT) × MSS	0.37	-0.32 – 1.07	0.275						
%ΔAeSR	Group (SIT)	-62.27	-205.63–81.10	0.377	0.26/0.08	Group (SIT)	37.4	-85.69–160.49	0.536	0.23/0.13
	MAS	-35.75	-68.44 – -3.06	0.034		SRR	293.5	27.79 – 559.21	0.032	
	MSS	11.85	-12.30 – 36.00	0.319						
	Group (SIT) × MAS	20.12	-22.94 – 63.17	0.342		Group (SIT) × SRR	-139.71	-506.31–226.89	0.439	
	Group (SIT) × MSS	-1.35	-36.47 – 33.78	0.937						
%Δvpeak	Group (SIT)	-1.38	-6.94 – 4.17	0.610	0.11/-0.11	Group (SIT)	1.37	-3.15 – 5.89	0.537	0.16/0.06
	MAS	-0.7	-2.06 – 0.66	0.297		SRR	9.19	-0.58 – 18.95	0.064	
	MSS	0.23	-0.61 – 1.08	0.572						
	Group (SIT) × MAS	0.12	-1.85 – 2.09	0.901		Group (SIT) × SRR	-6.42	-19.89 – 7.05	0.334	
	Group (SIT) × MSS	0.16	-1.12 – 1.44	0.801						

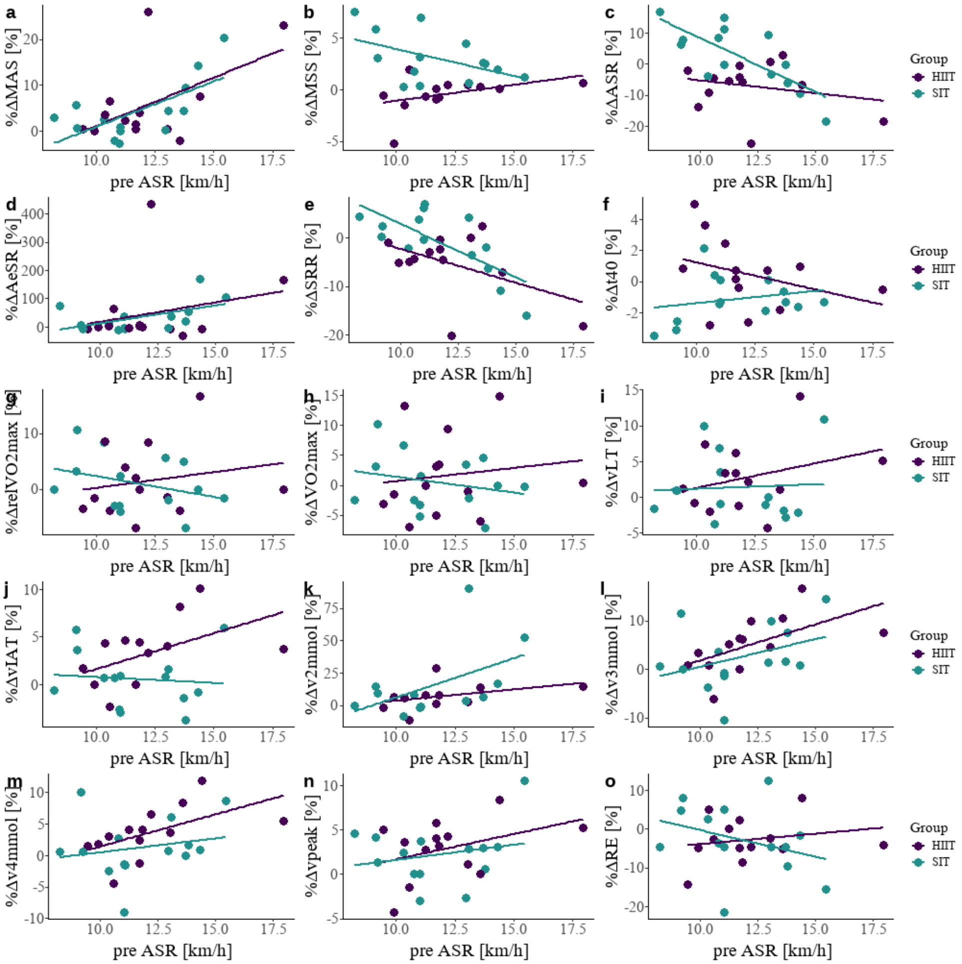
SIT – Sprint interval training group; MAS – Maximal aerobic speed; MSS – Maximal sprinting speed; ASR – Anaerobic speed reserve; AeSR – Aerobic speed reserve; SRR – Speed reserve ratio; t40 – 40-m-sprint time; $\dot{V}O_2max$ – Maximal oxygen uptake; vpeak – Maximal velocity in treadmill test; 95% CI – 95% confidence interval; p - significance value (bold are $p<0.05$), R^2/adj. R^2 – (Adjusted) explained variance.

20 Paper VI Supplementary Table 3: Results of moderator analyses with MAS and MSS as well as SRR as moderators with physiological variables.

	Group x pre-MAS + Group x pre MSS					Group x pre-SRR				
		beta	95% CI	p	R^2/adj. R^2		beta	95% CI	p	R^2/adj. R^2
%ΔtrelV̇O₂max	Group (SIT)	-3.51	-13.21 – 6.19	0.46	0.07/-0.15	Group (SIT)	6.63	-0.98 – 14.25	0.085	0.19/0.09
	MAS	-0.91	-3.29 – 1.48	0.438		SRR	15.46	-0.98 – 31.91	0.064	
	MSS	-0.06	-1.55 – 1.42	0.929						
	Group (SIT) × MAS	1.98	-1.46 – 5.43	0.245		Group (SIT) × SRR	-25.07	-47.76 – -2.38	0.032	
	Group (SIT) × MSS	-0.25	-2.49 – 1.99	0.818						
%ΔV̇O₂max	Group (SIT)	-5.14	-15.23 – 4.94	0.301	0.07/-0.15	Group (SIT)	5.43	-2.61 – 13.48	0.176	0.17/0.06
	MAS	-0.76	-3.23 – 1.72	0.533		SRR	15.27	-2.10 – 32.64	0.082	
	MSS	-0.24	-1.78 – 1.31	0.753						
	Group (SIT) × MAS	1.73	-1.86 – 5.31	0.328		Group (SIT) × SRR	-23.19	-47.15 – 0.78	0.057	
	Group (SIT) × MSS	0.15	-2.17 – 2.48	0.893						
%ΔvLT	Group (SIT)	-3.78	-11.67 – 4.11	0.331	0.11/-0.10	Group (SIT)	2.07	-4.45 – 8.60	0.517	0.14/0.03
	MAS	-1.33	-3.27 – 0.60	0.167		SRR	12.19	-1.90 – 26.28	0.087	
	MSS	0.22	-0.99 – 1.42	0.712						
	Group (SIT) × MAS	1.37	-1.43 – 4.18	0.321		Group (SIT) × SRR	-11.34	-30.78 – 8.10	0.240	
	Group (SIT) × MSS	-0.07	-1.89 – 1.75	0.940						
%ΔvIAT	Group (SIT)	-2.35	-7.59 – 2.88	0.361	0.26/0.09	Group (SIT)	0.46	-3.87 – 4.79	0.828	0.29/0.20
	MAS	-0.86	-2.14 – 0.43	0.181		SRR	8.96	-0.38 – 18.31	0.059	
	MSS	0.54	-0.26 – 1.34	0.175						
	Group (SIT) × MAS	0.79	-1.07 – 2.65	0.388		Group (SIT) × SRR	-10.81	-23.71 – 2.08	0.096	
	Group (SIT) × MSS	-0.52	-1.73 – 0.68	0.377						

%Δv2mmol	Group (SIT)	14.49	-24.48 – 53.47	0.444	0.28/0.07	Group (SIT)	-1.31	-30.92 – 28.29	0.927	0.26/0.15
	MAS	-1.84	-11.24 – 7.56	0.685		SRR	20.4	-56.35 – 97.14	0.584	
	MSS	1.73	-4.17 – 7.63	0.545						
	Group (SIT) × MAS	-5.19	-16.68 – 6.29	0.354		Group (SIT) × SRR	43.94	-52.42 – 140.31	0.352	
	Group (SIT) × MSS	3.54	-5.13 – 12.22	0.401						
%Δv3mmol	Group (SIT)	-4.5	-13.55 – 4.55	0.313	0.32/0.16	Group (SIT)	1.52	-6.48 – 9.51	0.698	0.25/0.15
	MAS	-2.04	-4.26 – 0.18	0.070		SRR	19.36	2.09 – 36.62	0.030	
	MSS	0.95	-0.43 – 2.33	0.167						
	Group (SIT) × MAS	0.4	-2.82 – 3.62	0.800		Group (SIT) × SRR	-12.19	-36.01 – 11.63	0.301	
	Group (SIT) × MSS	0.43	-1.66 – 2.52	0.673						
%Δv4mmol	Group (SIT)	-3.48	-10.50 – 3.54	0.315	0.24/0.06	Group (SIT)	1.1	-4.87 – 7.08	0.706	0.23/0.13
	MAS	-1.34	-3.07 – 0.38	0.12		SRR	13.2	0.29 – 26.10	0.045	
	MSS	0.66	-0.41 – 1.73	0.215						
	Group (SIT) × MAS	0.61	-1.89 – 3.11	0.617		Group (SIT) × SRR	-11.33	-29.14 – 6.48	0.201	
	Group (SIT) × MSS	0.01	-1.61 – 1.63	0.987						
%ΔRE	Group (SIT)	4.46	-8.50 – 17.43	0.482	0.07/-0.16	Group (SIT)	4.29	-6.72 – 15.29	0.429	0.05/-0.07
	MAS	-0.17	-3.35 – 3.02	0.914		SRR	4.85	-18.91 – 28.61	0.677	
	MSS	0.52	-1.46 – 2.50	0.591						
	Group (SIT) × MAS	0.75	-3.86 – 5.36	0.738		Group (SIT) × SRR	-15.9	-48.68 – 16.88	0.326	
	Group (SIT) × MSS	-1.68	-4.68 – 1.31	0.255						

SIT – Sprint interval training group; %Δ – Percentage difference from pre to post; MAS - Maximal aerobic speed; MSS – Maximal sprinting speed; SRR – Speed reserve ratio; $\dot{V}O_2max$ – Maximal oxygen uptake; vLT – Velocity at base lactate; vIAT – Velocity at individual anaerobic lactate threshold; v2mmol/v3mmol/v4mmol – Velocity as corresponding lactate concentration; RE – Running economy; 95% CI – 95% confidence interval; p - significance value (bold values are $p<0.05$), R^2/adj. R^2 – (Adjusted) explained variance.



21 Paper VI Supplementary Figure 2: Interaction plots between ASR and percentage changes of outcome variables. HIIT – High-intensity interval training group; SIT – Sprint interval training group; %Δ – Percentage difference from pre to post; MAS – Maximal aerobic speed; MSS – Maximal sprinting speed; ASR – Anaerobic speed reserve; AeSR – Aerobic speed reserve; SRR – Speed reserve ratio; t40 – 40-m-sprint time; $\dot{V}O_2max$ – Maximal oxygen uptake; vLT – Velocity at base lactate; vIAT – Velocity at individual anaerobic lactate threshold; v2mmol/v3mmol/v4mmol – Velocity as corresponding lactate concentration; vpeak – Maximal velocity in treadmill test; RE – Running economy.

22 Paper VI Supplementary Table 4 Results of moderator analyses with ASR as moderators with locomotor variables.

	Group x pre-ASR				
		beta	95% CI	p	R^2/adj. R^2
%ΔMAS	Group (SIT)	0.05	-10.35 – 10.46	0.992	0.35/0.27
	ASR	2.12	0.39 – 3.84	0.018	
	Group (SIT) × ASR	-0.13	-2.56 – 2.30	0.912	
%ΔMSS	Group (SIT)	6.49	3.40 – 9.57	<0.001	0.55/0.49
	ASR	0.31	-0.20 – 0.82	0.224	
	Group (SIT) × ASR	-0.83	-1.55 – -0.11	0.026	
%ΔASR	Group (SIT)	18.56	6.47 – 30.64	0.004	0.52/0.46
	ASR	-0.82	-2.82 – 1.18	0.406	
	Group (SIT) × ASR	-2.68	-5.50 – 0.14	0.062	
%ΔSRR	Group (SIT)	0.1	-0.08 – 0.27	0.268	0.45/0.38
	ASR	-0.03	-0.06 – -0.00	0.024	
	Group (SIT) × ASR	-0.01	-0.05 – 0.03	0.67	
%Δt40	Group (SIT)	-3.51	-6.54 – -0.48	0.025	0.24/0.15
	ASR	-0.34	-0.85 – 0.16	0.171	
	Group (SIT) × ASR	0.5	-0.21 – 1.21	0.158	
%ΔAeSR	Group (SIT)	-3.08	-155.35 – 149.19	0.967	0.10/0.02
	ASR	13.6	-11.60 – 38.89	0.275	
	Group (SIT) × ASR	-1.2	-36.76 – 34.37	0.945	
%Δvpeak	Group (SIT)	0.32	-5.00 – 5.65	0.901	0.11/-0.01
	ASR	0.57	-0.31 – 1.45	0.195	
	Group (SIT) × ASR	-0.23	-1.47 – 1.02	0.708	

SIT – Sprint interval training group; MAS – Maximal aerobic speed; MSS – Maximal sprinting speed; ASR – Anaerobic speed reserve; AeSR – Aerobic speed reserve; SRR – Speed reserve ratio; t40 – 40-m-sprint time; $\dot{V}O_2max$ – Maximal oxygen uptake; vpeak – Maximal velocity in treadmill test; 95% CI – 95% confidence interval; p - significance value (bold are p<0.05), R^2/adj. R^2 – (Adjusted) explained variance.

23 Paper VI Supplementary Table 5:Results of moderator analyses with ASR as moderators with physiological variables.

	Group x pre-ASR				
		beta	95% CI	p	R^2/adj. R^2
%Δtrel$\dot{V}O_2$max	Group (SIT)	4.43	-4.91 – 13.76	0.337	0.07/-0.06
	ASR	0.56	-0.98 – 2.11	0.459	
	Group (SIT) × ASR	-1.31	-3.49 – 0.87	0.226	
%Δ$\dot{V}O_2$max	Group (SIT)	2.46	-7.37 – 12.28	0.61	0.04/-0.08
	ASR	0.44	-1.19 – 2.07	0.581	
	Group (SIT) × ASR	-0.97	-3.27 – 1.33	0.391	
%ΔvLT	Group (SIT)	0.85	-6.88 – 8.59	0.822	0.07/-0.05
	ASR	0.68	-0.60 – 1.96	0.283	
	Group (SIT) × ASR	-0.56	-2.36 – 1.25	0.529	
%ΔvIAT	Group (SIT)	0.69	-4.28 – 5.67	0.776	0.28/0.18
	ASR	0.75	-0.07 – 1.58	0.071	
	Group (SIT) × ASR	-0.88	-2.04 – 0.28	0.132	
%Δv2mmol	Group (SIT)	-5.16	-37.99 – 27.66	0.746	0.27/0.15
	ASR	1.72	-3.87 – 7.31	0.527	
	Group (SIT) × ASR	4.35	-3.51 – 12.20	0.261	
%Δv3mmol	Group (SIT)	-0.71	-9.75 – 8.34	0.873	0.26/0.16
	ASR	1.48	-0.02 – 2.98	0.053	
	Group (SIT) × ASR	-0.35	-2.46 – 1.77	0.738	
%Δv4mmol	Group (SIT)	0.04	-6.84 – 6.92	0.991	0.21/0.11
	ASR	1.02	-0.12 – 2.16	0.078	
	Group (SIT) × ASR	-0.58	-2.18 – 1.03	0.466	
%ΔRE	Group (SIT)	6.99	-5.29 – 19.27	0.251	0.09/-0.03
	ASR	0.54	-1.50 – 2.57	0.59	
	Group (SIT) × ASR	-1.91	-4.77 – 0.96	0.182	

SIT – Sprint interval training group; %Δ – Percentage difference from pre to post; MAS - Maximal aerobic speed; MSS – Maximal sprinting speed; SRR – Speed reserve ratio; $\dot{V}O_2$max – Maximal oxygen uptake; vLT – Velocity at base lactate; vIAT – Velocity at individual anaerobic lactate threshold; v2mmol/v3mmol/v4mmol – Velocity as corresponding lactate concentration; RE – Running economy; 95% CI – 95% confidence interval; p - significance value (bold values are $p<0.05$), R^2/adj. R^2 – (Adjusted) explained variance.

Running is one of the most accessible of physical activity, yet performance in running-based sports depends on a complex interaction of different factors. This work explores how profiling can enhance our understanding of endurance performance and training individualization. It has three main aims: (1) to evaluate the value of locomotor and physiological profiling approaches for assessing athlete characteristics, (2) to assess the validity and reliability of testing methods for the locomotor profile, and (3) to examine how locomotor profiles influence acute and chronic responses to high-intensity interval training. Findings demonstrate that profiling approaches provide complementary perspectives, that applicability of profiling is shaped by methodological choices, and that profiles affect training tolerance and adaptation. This research highlights locomotor profiling as a promising tool for individualized performance monitoring and training prescription in endurance and running-based sports.

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